The Evolution and Environmental History of Wainono Lagoon, New Zealand

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Abstract

Coastal lagoons are dynamic environments that are sensitive to climate change, sea level rise and anthropogenic activities, including the use of catchment water resources and land. Their management is of high public and scientific interest at present, both locally and internationally, not least due to widespread water quality declines associated with resource use in feeder catchments. However, despite its importance for sustainable lagoon management, consideration of the lagoon morphology and long-term stability appears to have been neglected in the decision making processes to date.

This thesis provides the evolutionary and environmental history as well as a comprehensive understanding of the lagoon system and assessment of the long-term stability status of Wainono Lagoon, a coastal hydrosystem located in the South Island of New Zealand. The main objectives of the research are to: (i) reconstruct a history of the lagoon environment and morphological evolution over the historical time, (ii) identify the components that influence the lagoon system and morphology, (iii) assess the long-term stability of Wainono Lagoon and (vi) develop a generic evolutionary model for waituna-type lagoons.

The evolutionary and environmental history of Wainono Lagoon is reconstructed using a number of techniques including analyses of sediment cores, foraminiferal assemblages and anisotropy of magnetic susceptibility. Analyses of barrier beach profiles, aerial images and bathymetry of the lagoon were also used to establish the recent trends in lagoonal sedimentation and barrier beach morphology. A generic evolutionary model was developed which can be used to assess the long-term stability of waituna-type lagoons on a transgressive coast. This study has found that Wainono Lagoon has experienced an estuarine phase for a prolonged period of time at least once since the closure of the barrier. Today, despite the chronic erosion of the Canterbury Bight, the coast of Wainono Lagoon is relatively stable, with very slow translation of the southern part of the Wainono barrier. The lagoonal sedimentation rates are high relative to the rate of sea level rise meaning that if the current trends continue the lagoon will become filled with sediments over time. This highlights the necessity of monitoring of the sedimentation regime in the lagoon, which is hardly understood at present. Translation of the barrier further south along the Waihao

Dead Arm will cause blockages and management of this issue will also affect the future stability of Wainono Lagoon.

Management intervention can result in accommodation or hindrance in the natural evolution of waituna-type lagoons. At Wainono Lagoon, inadequate understanding of human impacts on the lagoon's geomorphology and a lack of adequate strategy may result in accelerated infilling of the lagoon. In development of a long-term policy and management strategies, it is critical that the morphological evolution and long-term stability status is taken into consideration in order to avoid undesirable outcomes such as human induced infilling of the lagoon. This study provides a better understanding of the dynamics of Wainono Lagoon as a basis for development of such a management policy and strategies.

Glossary of key Māori Terms

Iwi – Māori tribe

Hapū - Māori sub-tribe

Harakeke - flax

Mahinga kai – food gathering or traditional resource areas where food is gathered or produced

Mana - status/power

Māori – indigenous people of New Zealand

Ngāi Tahu – a Māori tribe of the South Island of New Zealand, including Canterbury.

Rūnanga - the governing council or administrative group of a Māori hapū or iwi

Tangata whenua – "people of the land'

Taniwha – a water creature of Māori legend

Te Kai Hinaki o Rakihouia (the food basket of Rakihouia)

whānau - family

wāhi taonga - sites of significance

wāhi tapu- sacred places

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Chapter 1. Introduction

1.1 Thesis statement

Waituna-type lagoons/coastal lakes on New Zealand's mixed sand and gravel coasts are highly dynamic environments that can experience dramatic evolutionary phases and morphological changes over time. These lagoons provide significant values, including in areas of biodiversity, fisheries, recreation and Māori culture, and therefore their management is of high public and scientific interest. Management strategies require the protection of those values as well as mitigation of hazards, including coastal erosion and hinterland flooding. In development of a long-term policy and sustainable management strategies, understanding of the lagoon system and effects of environmental changes on the lagoon morphology is crucial. However, consideration of the lagoon morphology and long-term stability appears to be very limited in the decision making processes to date.

This also applies to the international context. Management of coastal lagoons is also a topic of great interest not least because of the ever-increasing pressures on freshwater resources globally. Known issues associated with lagoon management include degradation of water quality, loss of ecological and economic values, loss of land associated with shoreline retreat and risk of inundation (e.g. Gonenc & Wolflin, 2005; Philomena, 1994; Pye & Blott, 2009). Comprehension of the evolutionary history and the effects of both natural and human induced environmental changes is crucial in order to sustainably manage the lagoons of significance and to avoid undesirable outcomes such as human induced degradation or loss of the lagoon.

This study investigates the evolutionary and environmental history of Wainono Lagoon in New Zealand, to increase our knowledge in the effects of anthropogenic activities and environmental changes on the lagoon morphology, which is essential for development of a sustainable management policy and strategies. Unlike other waituna-type lagoons such as Te Waihora/Lake Ellesmere in Canterbury and Waituna Lagoon in Southland, there is limited published research on the evolution and environmental history of Wainono Lagoon at present. Wainono Lagoon is smaller in size compared to Te Waihora or Waituna Lagoon, however, a better understanding of the lagoon system than currently exists is required as a high level of management intervention is currently applied to this site.

Wainono Lagoon and the surrounding wetland, which is the most extensive wetland in South Canterbury, are of national and regional significance. The area provides a habitat for waterfowl and numerous fish species such as eels/*tuna*, lampreys/*kanakana*, flounder/*pātiki*, smelt and *inanga* (Schallenberg & Saulnier-Talbot, 2014). Since the Lower Waitaki Zone Implementation Programme (ZIP) outlines the improved ecosystem health of Wainono Lagoon as a primary objective, numerous government organisations, local rūnanga and numbers of interested parties have been involved in the Wainono Lagoon Restoration Project to improve the water quality and enhance biodiversity (Environment Canterbury, 2012). The restoration of Wainono Lagoon is not only relevant to water quality and biodiversity, but also relevant to the Māori cultural values attached to the lagoon (Te Runanga o Waihao, n.d.). The lagoon management also needs to incorporate hazard management to mitigate the risk of sea water inundation into the surrounding farmland. Therefore, the sustainable management of Wainono Lagoon requires a long-term policy based on the understanding of their dynamic nature and sensitivity to climate change, sea level rise and human activities including the water resource use and land use within the catchment. This study provides a better understanding of the dynamics of Wainono Lagoon as a basis for development of such a management policy and strategies.

1.2 Conceptual context

This section presents the review of existing literature in lagoon studies and introduces important concepts that are relevant to this study.

1.2.1 Coastal lagoons

The definition of coastal lagoons adopted here is that of Kjerfve (1994, p. 1), defined as "*inland water bodies, …usually oriented parallel to the coast, separated from the ocean by a barrier, connected to the ocean by one or more restricted inlets, and have water depths which seldom exceed a few of meters. A lagoon may or may not be subject to tidal mixing, and salinity can vary from that of a coastal fresh-water lake to a hypersaline lagoon, depending on the hydrologic balance. Lagoons formed as a result of rising sea level mostly during the Holocene and the* *building of coastal barriers by marine processes*". Bird (2008, p. 311) provided additional insight into above definition: "*Coastal lagoons are areas of relatively shallow water that have been partly or wholly sealed off from the sea by the deposition of spits or barriers, usually of sand or shingle, built up above high tide level by wave action*" and also excluded those lagoons "*enclosed by coral reefs, either between barrier reefs and the land or within atolls which are best regarded as marginal marine environments linked with the open sea at high tide*".

The study of lagoon sediment processes was primarily focused on 'morphology and evolution' between the 1920s and 1940s. Since the late 1940s, 'characterisation' began to be incorporated into the study and knowledge of lagoon sediment processes, followed by 'processes' from the mid-1950 and 'systems' from the 1960s. The trends in lagoon studies since the 1920s show that the thinking has shifted from that lagoons are 'a passive depositional environment where a barrier protects from the ocean wave energy' to 'the dynamic environment having erosion and deposition events involving the tide, wind and biogenic activity' (M. N. Nichols & Boon, 1994).

Zenkovich (1967) presented a theory of 'small and large rivers' which is based on the river-derived sediment load in relation to the stability trend of the adjacent coastal morphology. A 'large river' produces abundant sediment load to accrete or sustain the position of its adjacent coast against abrasion loss and longshore drift of sediments. In contast, the sediment load of a 'small river' is insufficient and unable to maintain its coastal position against overpowering marine forces including coastal erosion. The rivermouth morphology and lagoon/estuary geometries are also dominated by marine processes. Kirk (1991) who studied the dynamics of the Rakaia River mouth stated that this small river theory is relevant to many coastal lagoons in Canterbury including Rakaia. It was also noted that little had been published concerning small rivers while large rivers had been more comprehensively studied, particularly those with deltas.

The adjacent coast of Wainono Lagoon is clearly dominated by marine processes. The fluvial sediment load is small, which derives from the Hook River, Waituna Stream and artificial drains with occasional supply from the Dead Arm (the catchment is described in detail in section 2.4). It is argued here that the Wainono area which includes the Waihao River needs to be considered as one lagoon/wetland system and the whole coastal morphology is a product of multiple 'small rivers' in the area. The area between Willowbridge and the Makikihi River consisted of extensive swamps prior to changes in land-use in the late 19^{th} Century (Studholme, 1940). There is a possibility that the river fed into the swamps developing a hapua type elongated lagoon from the mouth of the Waihao River towards North, eventually connecting to the mouths of Sir Charles Creek, Waimate Creek and Wainono Lagoon. However, this hypothesis is beyond the scope of this research.

1.2.2 Coastal barriers

The morphology of the barrier plays a significant role in lagoon dynamics and, consequently, in lagoon management. Beach, dune, shoreface, inlet, washovers and tidal delta, in some cases, are the common facies forming barrier morphologies (Masselink & Hughes, 2003). The barrier morphology largely governs the lagoon hydrology which has effects on the lagoon/estuary classification itself and other components such as hazard and ecology. Ultimately, a waituna-type lagoon does not exist without a barrier or spit. In this section, the dynamics and processes of coastal barriers are explored in order to understand the role barriers play in lagoon dynamics.

Development

Formation of barriers and spits is complex and there has been a debate in the scientific literature over this subject. Cotton (1949) assumed that longshore drift is the driver of the growth of all barrier spits. This means that two opposing recurved spits, seen at Ohiwa Harbour entrance for example, are developed by two opposing drift systems. Today it is understood that opposing spits can be formed by tidal flow at the inlet together with the consequential effects of wave refraction (Kirk, 1992a). Zenkovich (1967) argued that majority of the lagoons and coastal barriers have resulted from the transgression and sea level rise over the last 15,000 years. Also in 1967, Hoyt realised that classic Johnsonian theories of barrier formation from offshore bars (Johnson, 1919) did not substantiate the empirical data. He proposed a hypothesis that barrier islands were formed during the late Holocene sea level rise, which flooded the shore around a subaerial dune, and during the slow submergence a ridge of sediment deposits previously formed immediately landward of shoreline became a barrier separating the lagoon from the sea (Hoyt, 1967). This theory was questioned by Fisher (1968) who argued that barrier islands are developed as

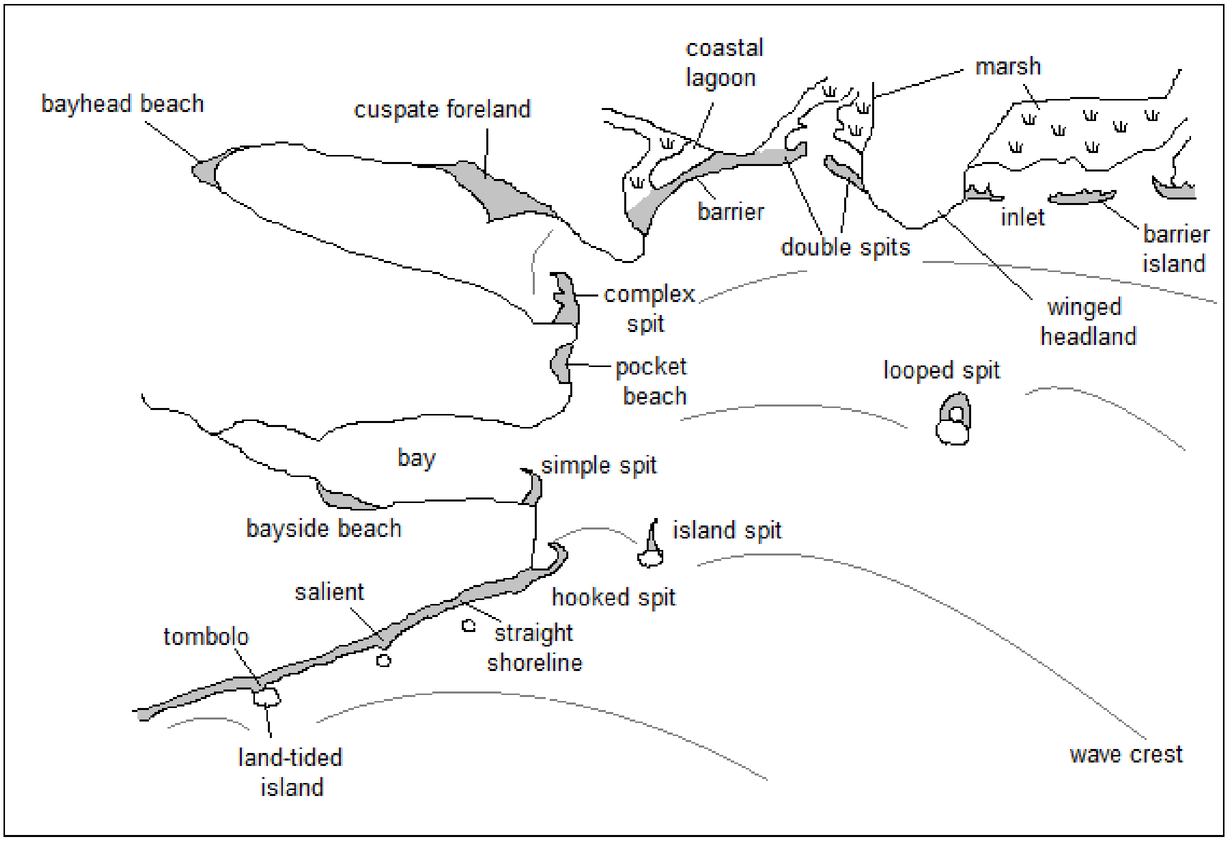


Figure 1.1. Morphology of barriers and spits. Schematic distribution of features in relation to wave approach. (Modified from Woodroffe, 2003, p. 301)

complex spit chains on the shoreline of submergence. Fisher also acknowledged that there appeared to be more than one type of barrier islands. After all, the view of "multiple causation" prevailed (R.W.G. Carter, 1988). Today, it is known that both longshore drift and transgressive movement of sediment are important in the development of spits and barriers. Other factors influencing the barrier development are the pattern of sea level change, geometry and sediment properties (Matias, Blenkinsopp, & Masselink, 2014; Woodroffe, 2003). Various types of spits and barriers based on the features recognised by Johnson (1919) are shown in Figure 1.1.

The current knowledge on gravel dominated barrier evolution is limited internationally. Lagoon barriers on a gravel dominated coast develop on mid to high-latitude coasts. In many cases, sediment sources of these lagoon barriers are glacigenic deposits and the coasts are deemed *paraglacial*. The coasts of the South Island of New Zealand are *fluvio-glacial*. Much of the study in evolution and breakdown of paraglacial coastal barriers has been focused on the east coast of England (Pye & Blott, 2009), southeast coast of Canada, eastern Nova Scotia and south coast of Ireland (R. W. G. Carter et al., 1989; Forbes, Orford, Carter, Shaw, & Jennings, 1995). Orford, Carter, and Jennings (1991) recognised three stages in the development of coarse clastic barriers on a paraglacial coast: initiation of drift aligned forms under sea level rise, followed by stabilisation with a shift into swash aligned form and finally the break-down of barrier triggered by sediment starvation and/or sea level rise. An evolutionary typology self-organisation and transition of gravel dominated barriers was suggested by Forbes, Orford, Carter, Shaw and Jennings in 1995 (Figure 1.2). These insights have advanced the understanding of the barrier behaviour on coarse clastic coasts. However, it is still unknown why and how these transitions of a barrier occur. The model has also been developed on limited examples and it is unknown if the model is applicable to mixed sand and gravel barriers as Kirk (1991) stresses that mixed sand and gravel coastal dynamics are more complex.

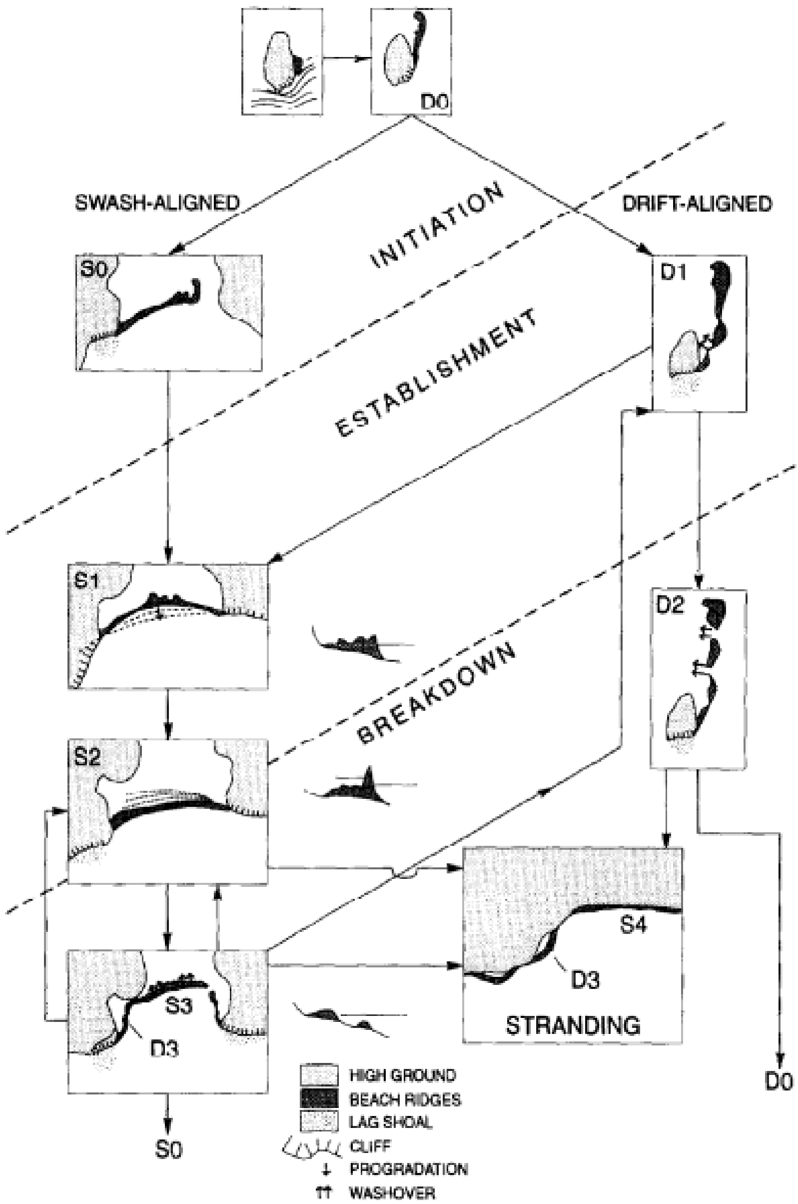


Figure 1.2. Evolutionary typology of coarse clastic barriers on transgressive coast. (Source: Forbes et al., 1995, p. 68)

Storms

Significant changes in gravel/mixed sand and gravel barrier morphology often occur during storm events. Overwash during storms results in evolution of gravel dominated barrier by outlet formation (Hart, 2007), barrier breaching, barrier breakdown (Pye & Blott, 2009) and long-term migration of the barrier through the 'rollover' mechanism (Matias et al., 2014; Orford & Carter, 1982). The significance of storm events in the coastal morphology in South Canterbury is also highlighted by Gerslov (1991) and Hewson (1977), which is discussed in more detail in Chapter 2 (section 2.5). Storms also cause changes in other hydrological components such as increased lagoon level associated with rainfall and higher sea level due to low atmospheric pressure. This makes prediction of the future trend in barrier morphology difficult (Orford et al., 1991).

Significant morphological changes were observed during controlled extreme events in prototype-scale laboratory experiments in 2008 (Whitehouse, 2012). Increased intensity in storm-like condition by controlling parameters, including mean sea level, wave height, lagoon depth and peak wave period, resulted in both overtopping and overwash. The study found that overtopping increases the height of barrier crest, steepens the beach face and shifts the beach step landward which results in increased run-up. This process creates a condition that leads to an overwash and consequent rollover of the barrier (Matias, Williams, Masselink, & Ferreira, 2012). This process is highly pertinent to the Wainono barrier. At Wainono, it was found that the steep foreshore and backshore slopes also makes the barrier prone to breaching (Stapleton, 2005).

The wave run-up during storms is also relevant to the interpretation of former sea levels. Some studies used preserved ridges to infer the former shorelines (e.g. Armon, 1974). However, recent study acknowledges that preserved ridges do not indicate the former sea levels but are more related to the wave run-up height during high energy events (Orford et al., 1991). This concept is also evident in the study by Armon (1974). He concluded that the preserved ridges relate to the positions of a former shoreline in the Te Waihora/Lake Ellesmere area, however, the high energy wave environment needs to be taken into consideration in reconstructing the former sea levels. It is likely that highest ridge crests were formed during storm events with higher wave run-up.

Barrier response to rising sea level

Fluctuation of sea level is one of the major drivers of dynamic coastal morphology. Generally, a falling sea level results in progradation of a shoreline. On the other hand, sea level rise generally results in transgression of the shoreline (Masselink & Hughes, 2003). A basic model of barrier response is introduced here to understand the impacts of sea level rise on a coastal barrier and lagoon morphology. There are three ways a coastal barrier can respond to the rising sea level (Figure 1.3):

(1) Barrier translation: The barrier moves landward across the substrate gradient without loss of material. This occurs by the 'washovers' process when the sediments eroded from the shoreface is deposited behind the barrier. This is a roll-over model presented by onshore sediment transport.
(2) Barrier erosion: This model (also known as Brunn rule) involves offshore sediment transport. The rise in sea level erodes the shoreface and deposits the sediment below the wave base in the nearshore zone. The shoreface maintains the cross-sectional geometry and the entire profile moves upward.
(3) Barrier overstepping: The original barrier gets drowned on the sea bed as a relict feature when the sea level rises too fast for the barrier morphology to respond. Minor onshore sediment transport is involved.

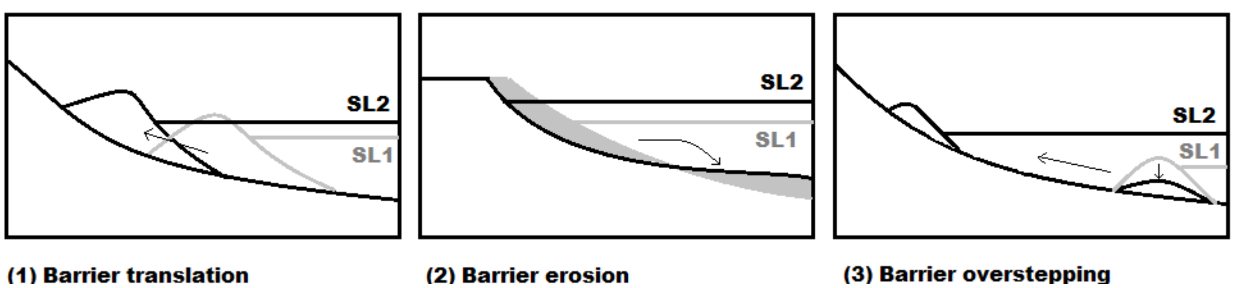


Figure 1.3. Barrier responses to sea level rise. (Modified from Masselink & Hughes, 2003, p. 246)

1.2.3 Long-term lagoon stability status

The long-term stability status of a coastal lagoon depends on the relative rates of sea level rise and sediment infilling (Kirk & Lauder, 2000; M. M. Nichols, 1989; M. N. Nichols & Boon, 1994; Schallenberg, Goff, & Harper, 2012). Despite the common view that coastal lagoons are sediment sinks and become filled over geological time (Woodroffe, 2003), Nichols (1989) who studied 22 lagoons in the United States found that majority was in the equilibrium accretionary

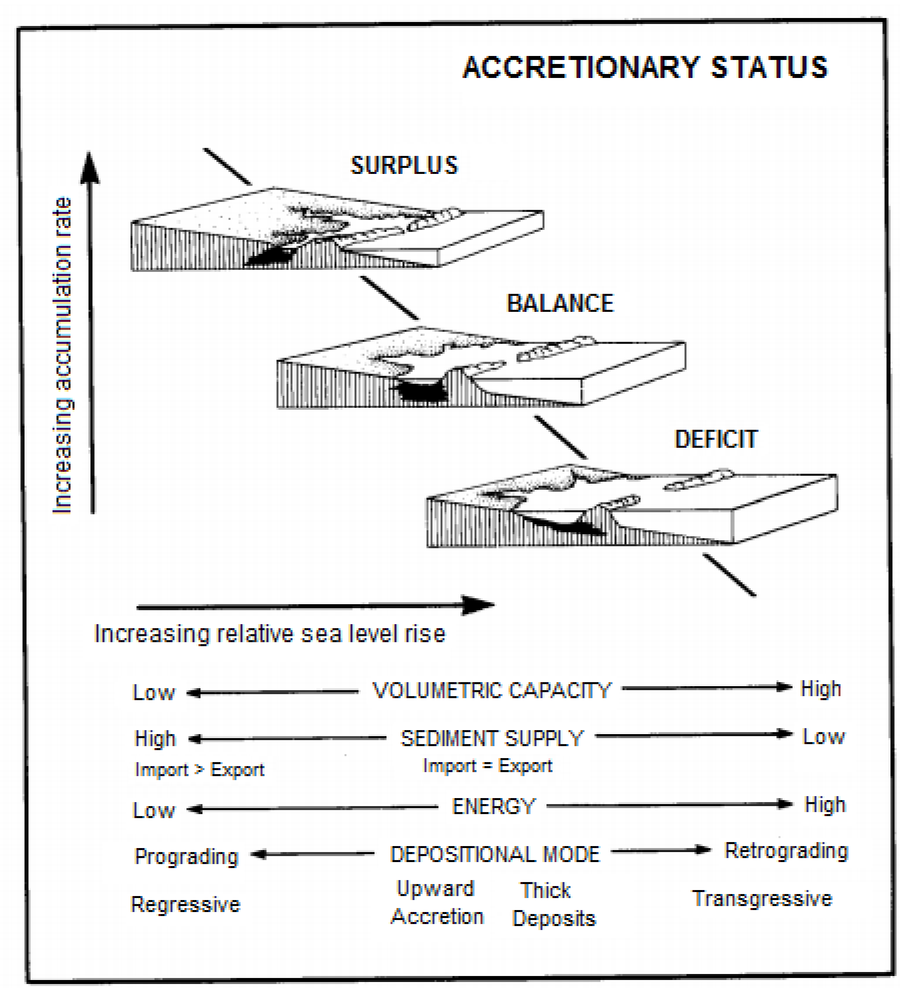


Figure 1.4. Nichols' (1989, p.215) schematic model illustrating the accretionary status from a 'surplus' (sedimentation rate > relative sea level rise) to a 'deficit' lagoon (sedimentation rate < relative sea level rise) in relation to the increasing rate of sediment accumulation and increasing rise of relative sea level.

state. Nichols (1989) suggested that coastal lagoons be classified on the basis of their accretion status as Figure 1.4 illustrates. Surplus lagoons can occur with infilling of marine deposited sediments or fluvial deposits. Deficit lagoons occur where the rate of submergence is greater than the rate of sediment infilling. When the rate of infilling keeps pace with the rate of submergence, theoretically the lagoon volume capacity is maintained.

The long-term stability of the lagoon is a simplified model. A stable lagoon, in terms of sedimentation rates against the rates of sea level rise, does not necessarily represent a sustainable environment. As discussed earlier, the rising sea level results in the landward movement of a barrier (Figure 1.3) unless the marine deposits continue to accrete the coast. It is important to note that the lagoon shoreline must retreat for the lagoon to maintain its volume when the barrier rolls over. Retreating shoreline may pose loss of farm lands and increased flood risk to human habitats and infrastructure. Lagoon retreat occurs at hapua lagoons where the barrier and lagoon shoreline are translating landward by coastal erosion (Hart, 2009; Kirk & Lauder, 2000). Lagoon retreat at waituna-type would not be by erosion of the lagoon shore but can occur by increased water level inundating the surrounding area. For a waituna-type lagoon on a transgressive coast to achieve a true equilibrium state, it will require accretion of the coast at the rate of sea level rise and inundation of the surrounding land in order to maintain the lagoon size. Nichols' model (1989) does not differentiate the fluvial and marine deposited sediments although fluvial sediments and marine sediments have different impacts on a lagoon.

Woodroffe (2003) states that coastal lagoons are, on a geological time scale, transitory features that are governed by sea level, climate and tectonic setting. It is added here that Human intervention with the local sediment supply, both fluvial and marine derived, also has a significant role in the lagoon stability. Two differing examples from the South Island, New Zealand, are presented here to display how anthropogenic component can affect the sediment supply. Washdyke Lagoon, on the east coast of South Island, has been severely affected by an alteration of the coastal landform. The lagoon shrunk in size by 80% between 1881 and 1984 despite the lagoon is on the eroding Canterbury Bight with the rising sea level. It is likely that this shrinkage is associated with the construction of the Timaru Port breakwater affecting the beach sediment supply (Kirk & Lauder, 2000). On the other hand, human activities can also increase sediment supply. Schallenberg et al. (2012) studied the environmental changes at Lake Waihola, on the south-east coast of South Island, and found that the pre-European sediment accumulation rates were 30 times less than the present day rates. It is suspected that sedimentation rates have been accelerated in recent decades due to vegetation clearance and expansion of agricultural use.

It is important to understand that both natural and human components affect the lagoon systems. Vulnerability of coastal lagoons on mixed sand and gravel coasts in New Zealand has been repeatedly highlighted by coastal researchers (e.g. Hart, 1999, 2007, 2009; Kirk, 1991; Kirk & Lauder, 2000; Todd, 1983).

1.2.4 Classification of coastal lagoons

Across the globe, for coastal lagoons characterised by sporadic closures and openings, various local terms are used in recognition of the regional characteristics that influence the hydrosystems. In Australia, for example, wave and river process dominated coastal lagoons which intermittently open and close are termed ICOLLs (intermittently closed and open lakes and lagoons). The term ICOLLs is used to recognise the distinctive characteristics of the estuaries in temperate Australia, that are strongly influenced by periodic flood and fire regimes, differing from those in the Northern Hemisphere (Roy et al., 2001). With isolated occurrences on the Victorian south coast and south-west Western Australia, the majority of ICOLLs are located along the south-east coast of Australia. Some of these ICOLLs are predominantly closed with occasional openings during drought conditions (Haines, Tomlinson, & Thom, 2006), and in Australia, ICOLLs typically occur on sandy coasts (NSW Department of Primary Industries, n.d.). However, in South Africa, the term TOCEs (temporarily open/closed estuaries) is used to distinguish the estuaries/lagoons that experience such closures from the permanently open estuaries (POEs). TOCEs, which include river mouths and coastal lakes, become separated from the sea by formation of sand berms (van Niekerk, 2007). The terms ICOLLs and TOCEs have been developed to recognise the distinctive characteristics in terms of climate and catchment regimes. In New Zealand, however, coastal lagoons have their own climate and catchment characteristics that differ from those of ICOLLs or TOCEs. Therefore, the terms ICOLLs or TOCEs are not used for the New Zealand coastal lagoons that experience sporadic closures and openings in this study.

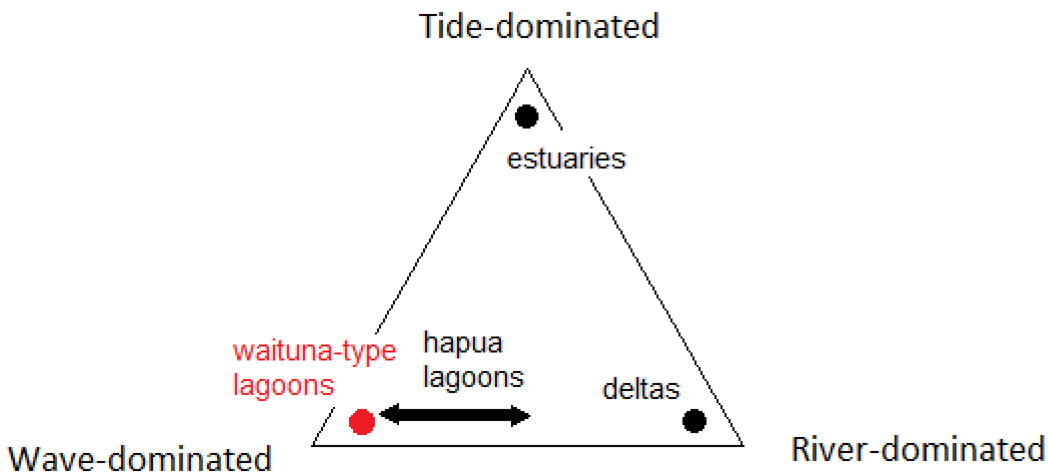


Figure 1.5. River mouth classification based on the principal process agents of waves, tides and rivers. Waituna-type lagoon has been added to the original diagram of Hart's. (Modified from Hart, 2007)

In New Zealand, the classification of coastal/river mouth waterbodies, such as lagoons, estuaries and deltas, has been the subject of debate. In 1988, Hume and Herdendorf classified the estuaries in New Zealand according to 16 morphological classes. Later, Kirk and Lauder (2000) argued that some of these so-called estuary classes are lagoons rather than estuaries and, as introduced earlier, classified these mixed sand and gravel coast lagoons into two categories: *waituna-type lagoon* and *hapua*. Hart (2007) also distinguished hapua lagoons, estuaries and deltas according to the principal process agents: tide, wave and/or river (Figure 1.5). The most recent classification of estuaries by Hume, Snelder, Weatherhead, and Liefting (2007), which is based on four different controlling constituents (climatic and oceanic; catchment processes; estuary-scale; and local hydrodynamic processes), recognises two hydrodynamic classes, known as coastal lakes/waituna-type lagoons and hapua lagoons.

Both waituna-type lagoons and hapua occur on New Zealand's mixed sand and gravel coasts where spits/barriers are developed by wave processes (Hart, 2007; Kirk & Lauder, 2000) (Figure 1.5). However, waituna-type lagoons and hapua differ primarily in terms of their geometry and relative volume of river inflow. Waituna-type lagoons typically develop in the coastal lowland

and is characterised by smaller river inflow in contrast to hapua lagoons which form at the mouth of relatively large rivers.

1.2.5 Waituna-type Lagoons

Waituna-type lagoons, which are relatively common on the mixed sand and gravel coasts of New Zealand, experience dramatic morphological changes over time. Some, but not all, coasts of waituna-type lagoons face chronic erosion. Coastal erosion plays a significant role in the morphology and environment of a waituna-type lagoon because the barrier, or parts of it, can be eroded and eventually open to connect the lagoon to the sea. In Canterbury, waituna-type lagoons are found on the Canterbury Bight, which is one such erosional coast. Te Waihora/Lake Ellesmere, located to the west of Banks Peninsula, and Washdyke Lagoon in South Canterbury are the most extensively studied waituna-type in Canterbury.

The evolutionary history of Te Waihora has been well established. Te Waihora was a bay when the sea level became similar to the present level approximately 5,000 years ago (Armon, 1970; Soons, Shulmeister, & Holt, 1997). A spit was developed due to the strong net northwards longshore drift and the present lagoon became an estuary approximately 4,000 years ago. Then the estuary was closed to become a coastal lagoon when the spit reached the northern end. The spit became a barrier and the lagoon became the presently known 'choked' lagoon. It is predicted that Te Waihora will open at the eroding southern end of the spit to become a bay within the next century (Hemmingsen, 1997; Kirk & Lauder, 2000). This scenario represents the deficit lagoon in Nichols' (1989) model illustrated in Figure 1.4.

Washdyke Lagoon is another waituna-type which has been affected by the accelerated coastal erosion. Washdyke Lagoon has shrunk in size from 253 hectares to 48 hectares since 1881 due to the rapid translation of the coastal barrier. The barrier retreat was caused by the reduced volume of coarse sediments reaching the barrier, which is most likely associated with the construction of the Timaru Port (Kirk, 1992b; Kirk & Lauder, 2000). This also represents the deficit lagoon in Nichols' (1989) model (Figure 1.4).

The evolutionary history of Wainono Lagoon is unknown at present. Since Wainono Lagoon is also a waituna-type lagoon developed on the Canterbury Bight, it could potentially become an estuary/bay or shrink in size and get filled in the future. The accretionary status of Wainono Lagoon is also unknown.

1.2.6 Evolutionary and environmental history of coastal lagoons

Reconstruction of past environments and evolutionary history of a barrier and lagoon complex on paraglacial/fluvio-glacial coasts has been recognised as an effective way of understanding the changes in climate, coastal and fluvial influences as well as the response of the coastal complex. The reconstruction of evolutionary and environmental history often involves multidisciplinary approach including analyses of sediment sequences, microfossils, pollen, radiocarbon/lead-210 dating from deposits, aerial photographs analysis and seismic investigation (e.g. J. B. Jensen & Stecher, 1992; Schallenberg et al., 2012; Soons et al., 1997).

In South Island, New Zealand, sediment core analyses have been conducted by numerous researchers to infer the historical environments. The Holocene environmental changes in Lake Waihola were investigated and summarised by Schallenberg et al. (2012). Evidence of mid Holocene highstand was preserved in a sediment core retrieved from Lake Waihola. It is argued that the long-term stability of this lake has been significantly affected by the combination of human activities and accelerated sea level rise in the recent decades. The Holocene evolutionary history of Te Waihora/Lake Ellesmere was studied by Soons et al. (1997) employing sediment core analyses in conjunction with aerial photographs, old maps and manuscripts to detect landform changes. Kain (2009) used a combination of analyses including aerial photographs and sediment cores to infer the recent environmental history of the sandy river-mouth lagoon systems in the west coast of New Zealand. Her study was not accompanied with the dating of sediments and therefore the timeframe is unknown. J. B. Jensen and Stecher (1992) used sediment cores in conjunction with shallow-seismic data to reconstruct the paraglacial barrier-lagoon evolution in the late Pleistocene Baltic Ice Lake. Mapping of subaqueous Pleistocene and Holocene deposits was completed and six evolutionary stages were identified. Multidisciplinary approach has been used nationally and internationally which provides a powerful tool in reconstructing the evolutionary and environmental history of a barrier and lagoon complex.

1.3 Previous research in the Wainono Lagoon area

Previous studies of the Wainono area have focused on the coastal erosion and morphology of the Waihao-Wainono barrier beach (Gerslov, 1991; Hewson, 1977; Single, 1992; Stapleton, 2005), with the exception of the recent environmental history of Wainono Lagoon by Schallenberg and Saulnier-Talbot (2014). The beach processes are important because they have a significant effect on the barrier morphology and thus on the lagoon morphology. Previous studies provide a good understanding in parts of the lagoon system, however, there is no published paper on the evolutionary history of Wainono Lagoon. This research considers the barrier beach, lagoon, and catchment as significant parts of the lagoon system and examines the present and past dynamics of Wainono Lagoon to understand the lagoon's behaviour under various influences including changes in sea-level, hydrodynamic conditions, and resource use in the catchment.

The coastal processes and sediment movement at the chronically eroding mixed sand and gravel coast in South Canterbury has been well documented (Gerslov, 1991; Hewson, 1977; Neale, 1987; Single, 1992). A sediment budget model has been developed and the variability in across-shore sediment size has been described by Hewson (1977). The average erosion rate of the South Canterbury coast in 1977 was 0.93 m per year and the calculated annual recession rate was 0.59 m per year. Neale (1987) estimated the net transport rates which are dependent on the prevailing angle of wave approach. He found that 'slugs' of beach sediment were moving alongshore at a rate of approximately 1.4 km per year. This idea of slugs was also confirmed by Gerslov in 1992 who studied the meso-scale periodicity of coastal erosion in South Canterbury. Gerslov (1992) found that the long-term erosion is particularly exacerbated by southerly storms.

Single (1992) also examined the role of high energy events in determining beach morphology along the Wainono Lowland coast. He concluded that one of the long-term effects of high energy events is that overtopping, resulting in barrier crest lowering or breaching, causes retreat of the barrier crest and shoreline. Since the sediment supply is in deficit, the retreat is irreversible unless human intervention is performed. Single concluded that the volume of a barrier plays a significant role during high energy events. Larger volumes of sediment were believed to be more effective in protecting a beach. Stapleton (2005) studied the form and function of the Waihao-Wainono barrier and investigated why barrier breach occurs at certain sites. It was found, contrary to Single 1992, the breach sites had larger barrier volume compared to non-breach sites. The breach site had steeper lower foreshore slope and subsurface comprised of layers of coarse and fine sediments. She concluded that the variation in permeability, due to these layers, was the major driver of barrier breach. According to Stapleton (2005), the recent breach of Wainono Lagoon and associated flooding was recorded in 1985, 2001 and 2002. Flood events along the South Canterbury coast prior to 1985 have also been recorded, however, the exact area of floods and the breach of the lagoon is mostly uncertain.

The temporal changes in the Waihao-Wainono barrier profiles were analysed by Hicks and Todd (2003) and Stapleton (2005). The analyses showed that five of six profile survey sites along the Waihao-Wainono barrier showed an increase in width since 1977. The only site which had decreased in width was the Wainono Lagoon site, which is one of the sites where a barrier breach occurred in recent decades. It is concluded, however, it is difficult to determine a long-term trend in the beach/barrier profile change since storm events have large impacts on beach and barrier morphology. Beach overtopping has also been a common feature during large storms, which results in the barrier being 'rolled over' in the landward direction (Hicks & Todd, 2003; Stapleton, 2005). This process could affect the lagoon size overtime unless the landward lagoon shore is also retreating.

In 2014, an environmental history of Wainono Lagoon for the last 160 years was assessed by Schallenberg and Saulnier-Talbot. They linked the changes in biotic community and degradation of water quality with changes in the lagoon level and land-use in the catchment since the settlement of the Europeans in the mid nineteenth century. After the construction of the Waihao Box, introduction to salinity has changed the lagoon biota to more estuarine communities. The water level was lowered and the fringing wetland was altered by agricultural land. Changes in land-use resulted in increased sediment loads, nutrients and consequently eutrophication of the lagoon. The sedimentation rate, based on the sediment core from the centre of the lagoon, was estimated to be 3 mm per year during the last 160 years. Schallenberg and Saulnier-Talbot (2014) provided a detailed history in the post European settlement era. However, the lagoon condition in pre European times remains unknown.

1.4 Research gaps

When reviewing the barrier and lagoon studies literature, a number of research gaps have become apparent. First, the current understanding of the barrier evolution on mixed sand and gravel coasts is limited. The majority of the study has been focused on sandy coasts whereas only limited research has been conducted on gravel/mixed sand and gravel coasts (e.g. Hemmingsen, 1997; Kirk, 1992b; Matias et al., 2012; Orford et al., 1991; Stapleton, 2005). Let alone the development and dynamics of gravel/mixed sand and gravel barriers remain poorly understood. While recent studies have improved our understanding of lagoon and barrier dynamics on coarse clastic coasts, theories are based on limited examples from the northern hemisphere. Further study and a wider variety of examples are needed to support and further develop current theories and concepts. It is also necessary to examine whether theories based on the paraglacial coasts is applicable to the fluvio-glacial coasts.

Second, a holistic comprehension of the Wainono Lagoon system itself is lacking. Its evolutionary history is currently unknown and knowledge of its environmental history is limited to ecological studies covering the last 160 years. Therefore, to address this research gap, this study examines the lagoon system as a whole which incorporates multiple components and processes which are often studied independently.

In addition, this research explores a new area in the reconstruction of the evolutionary and environmental history of a coastal lagoon. To achieve this, energy environments and directions of historical currents are inferred from an analysis of Anisotropy of Magnetic Susceptibility (AMS). This methodology has not been used in the national lagoon study to date. This adds a significant component in the reconstruction of a lagoon history particularly establishing the marine influences during high energy events.

This study will contribute to the literature both nationally and internationally, not only by deepening our knowledge and understanding of the coastal lagoon system on a mixed sand and gravel coast but also by introducing a new methodology which can be applied to identifying significant events in a coastal lagoon setting.

1.5 Research questions

This research investigates the morphology and dynamics of Wainono Lagoon over the recent years and historical times to reconstruct the evolutionary and environmental history. Considering the length of sediment core that can be obtained with the proposed methodology (in section 3.3.1), it is estimated at least 300 years can be investigated in detail. Variation in energy environment, foraminiferal assemblage, sedimentation and morphological changes over time will be examined using a transdisciplinary approach. Understanding of the lagoon processes and dynamics in the current and past settings will allow prediction of possible future trends and future scenarios. This study will provide answers to the key questions listed below.

1. What has been the evolutionary history of Wainono Lagoon in the last 300 years?
2. What are the causes of environmental changes in the lagoon?
3. How did the bathymetry of the lagoon change in the recent years and what is the implication?
4. Have there been changes in the position of the lagoon shoreline in the recent decades?
5. What is the geomorphic state of the lagoon likely to be in the future?

1.6 Research objectives

It is important to understand the evolving nature of the lagoon as well as its vulnerability to human activities in order to sustainably manage the resources and values attached to the lagoon.

This study explores the evolutionary history of Wainono Lagoon focusing on the morphological changes under various energy environments. The main objectives of the research are to:

1. Reconstruct a history of the lagoon environment and morphological evolution over the historical time;
2. Identify the components that influence the lagoon system and morphology;
3. Assess the long-term stability of Wainono Lagoon; and
4. Develop an evolutionary model for waituna-type lagoons.

1.7 Thesis structure

This chapter introduced the purpose and objectives of this research as well as the relevant theories and previous researches. Relevant literature has been reviewed and research gaps have been identified.

Chapter 2 explores the background of the study area to deliver an overview of the physical environment and history. A comprehension of the catchment dynamics provides a basis for the interpretation of research data and prediction of possible future trends.

Chapter 3 introduces the methodology employed in this research to achieve the aims. The methodology section is divided into two parts according to the investigation relating to 'recent changes in geomorphology' and 'reconstruction of evolutionary and environmental history'. The results and interpretations from each part are presented in Chapter 4 and 5 respectively.

Discussion on the results, methodology, theoretical framework and application is presented in Chapter 6. The complexity and relationships of key driving forces within a lagoon system are analysed. The possible future trends are discussed and linked to future planning and management of waituna-type lagoons in a wider context.

Finally Chapter 7 summarises the findings of this research. The objectives and contributions of this research are evaluated and suggestions for future research are stated.

Chapter 2. Study area

2.1 Introduction

In order to establish a holistic view and comprehension of the Wainono Lagoon system it is essential to understand the catchment environment and components that influence it. Therefore this chapter will provide a detailed description of the catchment and explore the physical dynamics of it.

Wainono Lagoon is a waituna-type lagoon located on the east coast of the South Island, New Zealand (Figure 2.1). This lagoon and wetland complex is of regional and national significance for its birds and fish. The area is also of cultural significance for Ngāi Tahu as a traditional *mahinga kai* site (Schallenberg & Saulnier-Talbot, 2014), which is discussed further in section 2.8. A barrier, consisting of mixed greywacke sands and gravels Figure 2.2, separates the lagoon from the sea (Stapleton, 2005). Below the gravel material is a saturated substrate consisting of blue-grey silts, sands and clay. The lagoon drains from its south-east corner via the Waihao 'Dead Arm', which meanders for 3.4 km toward the south to the confluences of the Waimate Creek and Sir Charles Creek. It then flows parallel to the coastline for 4 km and out to sea via the Waihao Box drainage structure as shown in Figure 2.3 (Pemberton, 1980). This section of the Dead Arm gets blocked with overwashed deposits during the barrier breach (Gerslov, 1991). The Waihao Box, which was constructed in 1910 at the Waihao River mouth, is a fixed outlet to the sea (Figure 2.4). The lagoon water level has been lowered and salinity in the lagoon was increased since the construction of the Waihao Box (Schallenberg & Saulnier-Talbot, 2014).

Figure 2.1. Wainono Lagoon is located between the Makikihi and Waihao Rivers. The net northward longshore drift transports sediments from the Waitaki River.

Figure 2.2. Wainono Barrier with Wainono Lagoon on the left.

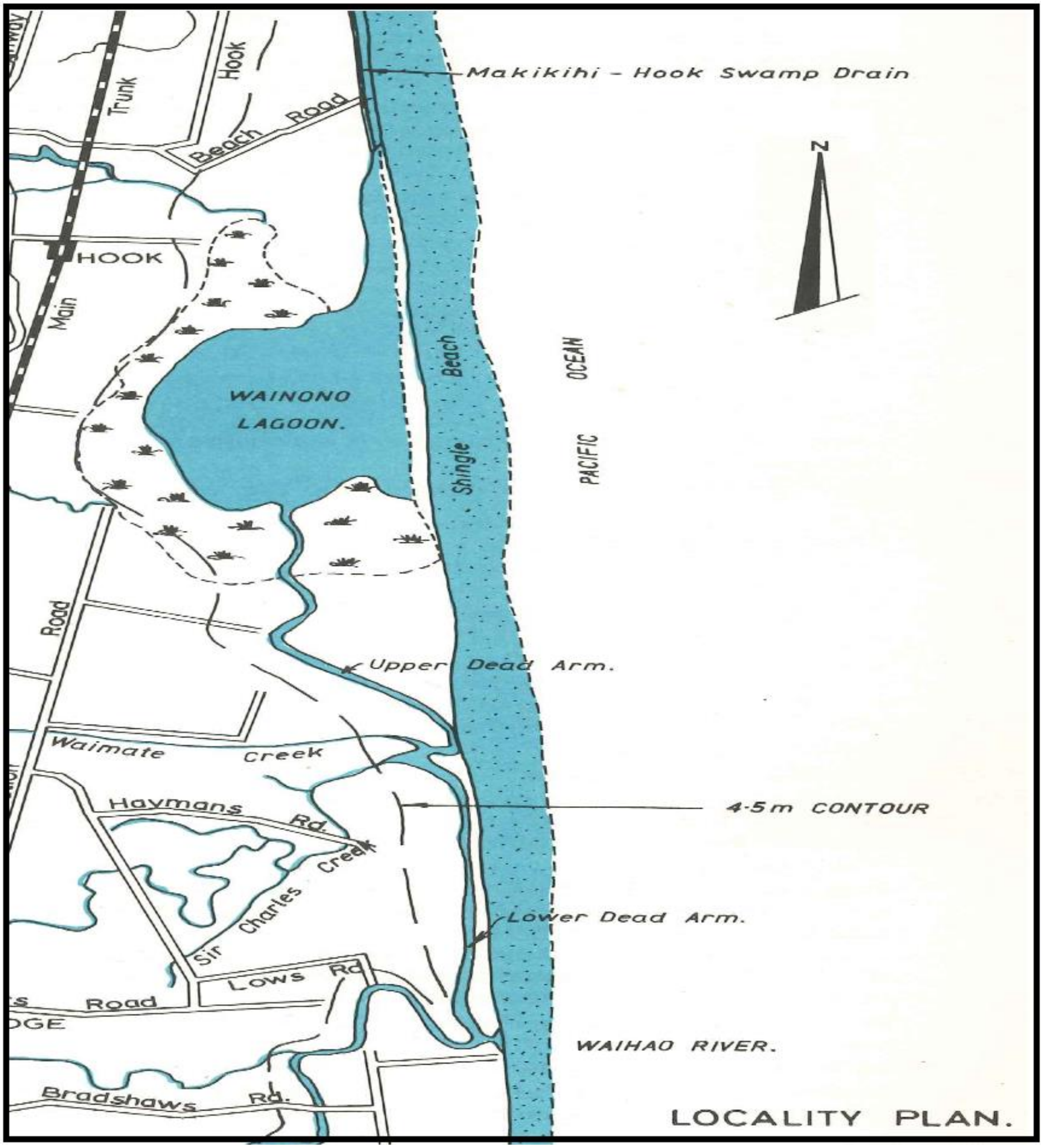


Figure 2.3. Locality Plan. (Source: Pemberton, 1980. pp.2)

(a)

(b)

Figure 2.4. (a)Waihao Box, date unknown. Circa 1910 (NZ Museums, n.d.) (b) Waihao Box in 2015. (Otago Daily Times, 2015)

2.2 Geology

The geology of the area is a major component that influences the coastal environment and surrounding hinterland. The South Canterbury coast between the Waitaki and Pareora Rivers is primarily composed of greywacke gravels with some schist and argillite derived from the Southern Alps in the late Pleistocene (20,000 – 70,000 years BP). The Southern Alps have been uplifted by plate motion on the oblique strike-slip Alpine Fault (Graham, 2008). As a result of uplift and topographic relief, sediments are lost from the Alps. The downlands (the rolling hill country) of South Canterbury comprise of younger sedimentary rocks including limestone and minor coal deposits (Gregg, 1979; Oborn, 1979; Suggate, 1978).

The Quaternary geology of the Wainono area has been influenced by the tectonic activity, as discussed earlier, but was influenced more significantly by the Pleistocene glacial activity. An extensive alluvial fan was constructed by a large sediment deposition via the Waitaki River. During glacial advances, the sea level was fallen and this resulted in progradation of the shoreline. The sea level rose again during interglacials. The rising sea level submerged parts of the coastline including the Waitaki river mouth which resulted in the erosion of the alluvial fan. The Holocene alluvial material is still present in the base of Wainono Lagoon and river beds in the vicinity (Hewson, 1977; Hicks & Todd, 2002).

The Canterbury Regional Council has summarised the complex geology of the area in descending order of age as detailed below (Durney & Aitchison-Earl, 2012):

1) Quaternary gravels and sands in river valleys.
2) Quaternary loess covering the downlands.
3) Kowai Formation Cannington gravels beneath these units.
4) Older Tertiary gravels and sand/siltstones encountered at depth (e.g. >200 m).

The Bluecliffs Silt, which is common around Wainono Lagoon, is “a blue-grey, sandy siltstone with thin, hard, sandy layers; pyrite concretions and films of gypsum. (The) overlying Southern Sand is a soft brown sandstone with hard layers and concretions” (Mutch, 1978, p. 510). The stratigraphy underlying Wainono Lagoon includes Quaternary loess, Quaternary alluvium, Quaternary silt, Cannington terrestrial silt, Cannington terrestrial gravel and Cannington marine

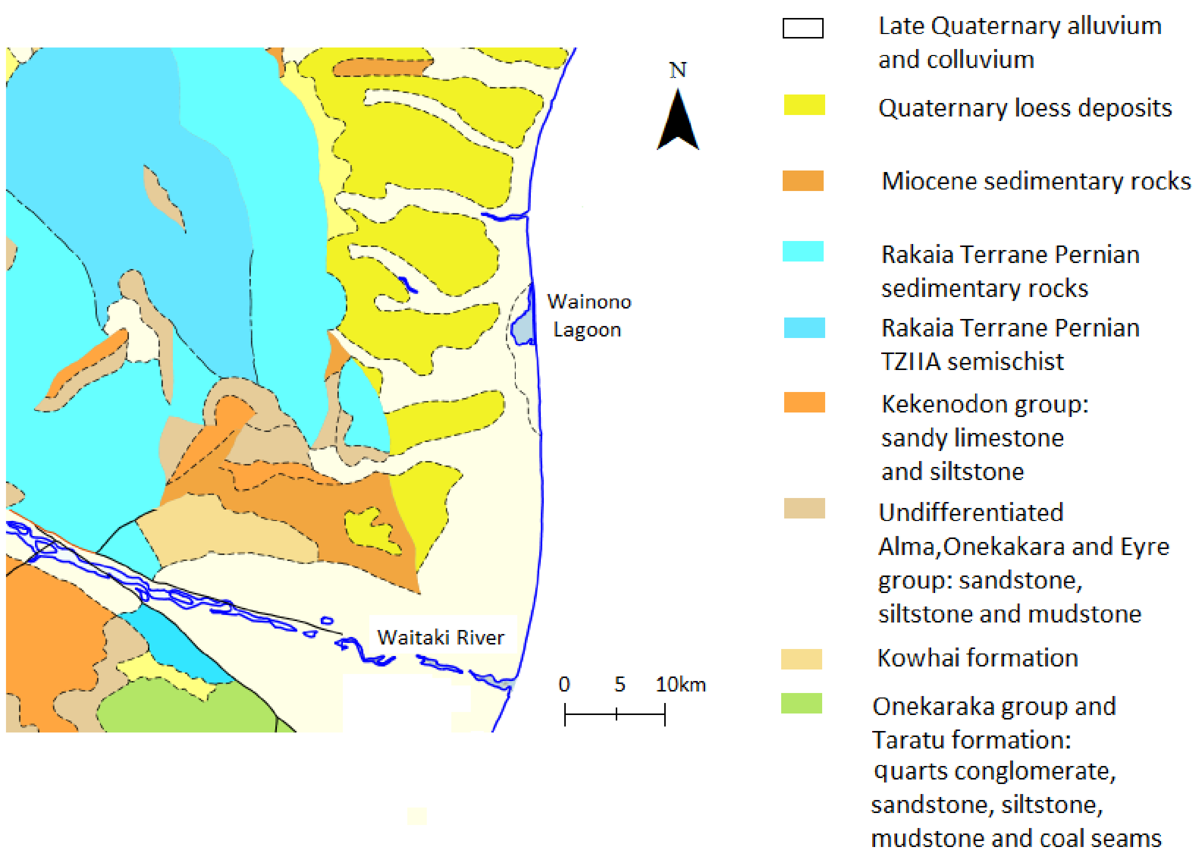


Figure 2.5. Geological map of the study area. (Modified from GNS Science, 2014)

gravel (Durney & Aitchison-Earl, 2012). A geological map of the area including the Wainono catchment is illustrated in Figure 2.5.

2.3 Climate

New Zealand lies between 34° and 47°S latitude and has a temperate climate. The average monthly temperature of the Waimate District, where Wainono Lagoon is located, varies between 6 and 16.3 °C (I. S. Jensen, n.d.). The monthly average rainfall records between 1951 and 2014 (Figure 2.6) indicate that Waimate typically receives relatively low (relative to other regions in New Zealand) but steady rainfall throughout the year. It could be argued that the rainfall in recent years has been lower compared to the 1951-1980 monthly average rainfall data, except the

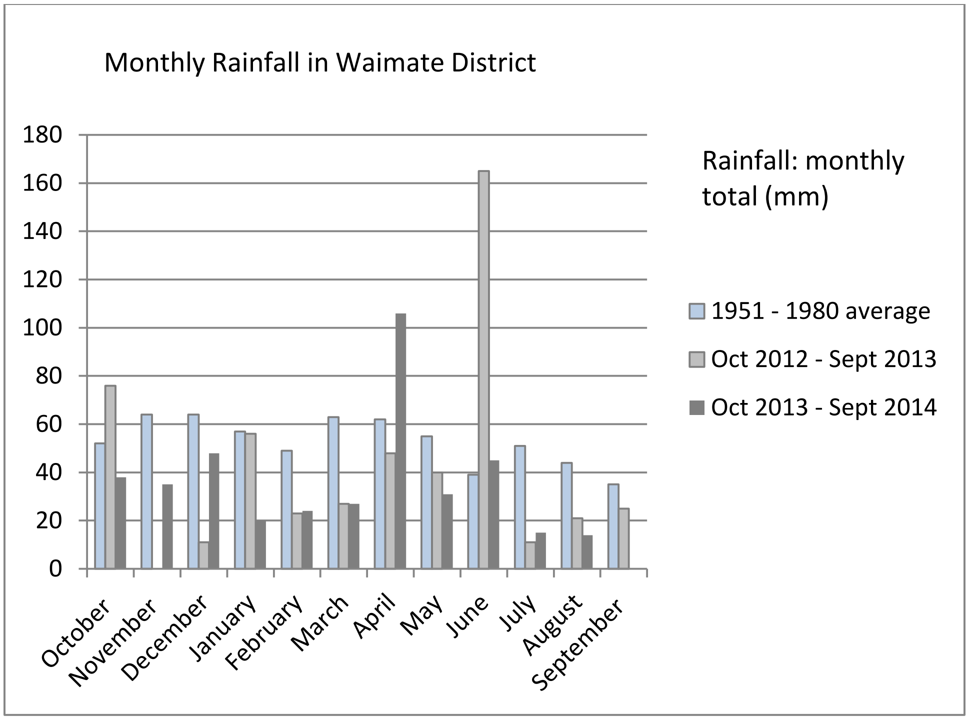


Figure 2.6. The rainfall normal for the period 1951 to 1980 in comparison to the recent years. (Data from Ryan, 1987, p.8 and Waimate District Council, 2014, p.16)

anomalies. NIWA reported that it is likely the drought risk in Canterbury Plains will increase by 10% by 2050 due to climate change (A. Clark, Mullan, & Porteous, 2011). This may increase the demand for irrigation water in the region, altering the hydrology of the area.

2.4 Hydrology

Wainono Lagoon has a surface area of 335 hectares and is surrounded by wetlands (Gerslov, 1991). The lagoon has a catchment area of 252 km^2 according to Pemberton (1980). The Hook River, Waituna Stream and numerous open drains discharge directly into the lagoon.

The Hook, Waituna, Waimate and Waihao Rivers are hill-fed rivers. They receive rainfall and runoff from the Hunter and Campbell Hills. They lose water as they flow across the alluvial fan before they discharge into Wainono Lagoon, the Dead Arm or the sea. Buchanans Creek and Sir

Table 2.1. Estimated mean outflow of Rivers and Creeks in the Wainono catchment. (Source: Aitchison-Earl, Ettema, Horrell, McKerchar, & Smith, 2006)

	Mean outflow (l/s) at or downstream of SH1
Hook River	522
Waimate Creek	0 or minor ponding
Sir Charles Creek	244
Buchanans Creek	355
Waihao River	3206

Charles Creek are spring-fed streams which discharge into the Waihao River and Dead Arm respectively. The Waihao River (catchment area of approximately 530 km^2) discharges into the sea via the artificial outlet called the Waihao Box, however, it also flows into Wainono Lagoon via the Dead Arm when the Waihao Box is closed, which is not a rare event. The Wainono catchment that is determined by Pemberton (1980) does not include the Waihao River. However, this study considers that the Waihao River is an important part of the Wainono Lagoon and wetland system.

The estimated mean outflows of the rivers in the Wainono catchment are summarised in Table 2.1. With the exception of the Waihao River, the inflows are relatively low. Relatively low river inflows and catchment-specific sediment yields are typical characteristics of waituna-type lagoons (Kirk & Lauder, 2000).

Although the volume is not exactly quantifiable, some water from the Morven Glenavy Ikawai Irrigation Scheme ends up in the Wainono-Waihao catchment. The exact effects are unknown, however, it is important to take this into consideration as groundwater and surface water receives excess irrigation water and runoff. Currently, a new irrigation scheme is being proposed to irrigate an area of 40,000 ha north of the Waitaki River. This may balance the predicted reduction in rainfall with irrigation runoff. The excess irrigation water will enter the groundwater and eventually flow into the Wainono Lagoon system. The scheme will also affect the flow in the Waitaki River, which is the source of irrigation water, and will consequently impact the sediment supply to the coast.

2.5 Sediment Supply

The coastline of South Canterbury is generally in a sediment-starved condition relative to the high energy coastal processes and is in a chronically erosional state. The shoreline began to retreat approximately 7,000 years BP after the Holocene sea level rise from its low stand at 120 m below the present sea level (Hicks, 2007). The chronic erosion is primarily natural but is exacerbated by anthropogenic activities today (e.g. Hewson, 1977; Hicks, 2007; Kirk, 1987). The Waitaki River has been in entrenching phases in the last 10,000 years causing reduced gravel sediment supply and associated coastal erosion. Although its exact effects have not been clearly detected on the coast, according to Hicks (2007, p. 3), the sediment load has also been reduced by 75% by damming of the Waitaki River for a hydroelectric development. An encroachment of exotic plant species, such as crack willow and gorse, has also choked the river to trap sediments.

The South Canterbury coast can be divided into sections with differing characteristics in terms of sediment budget and movement (Hewson, 1977). This highlights the importance of examining the coastal behaviour at a correct scale. The stretch between the Makikihi and Waihao Rivers is characterised by the net northerly movement of beach material and displays a high annual sediment turnover of 70%. According to Hewson's (1977) sediment budget above Mean Low Water Level, 66.4% of the beach sediment is transported by the longshore drift. The sediment contribution from cliff erosion in the Wainono Lowland coast is less than 1%. The nearshore transfers (onshore + and offshore -) account for 3.5% of the beach volume. The average annual rate of coastal change at the Waihao Box for the period 1910 to 1970 was calculated to be -0.45 m (Hewson, 1977, p. 102 Table 4). However, the data for the period 1864 to 2004 show that the coast along Wainono Lagoon is relatively stable with accretion in most parts (Hicks, Single, & Hall, 2006). The seasonal variation in the beach profiles is less of importance in the coastal morphology in this area since the majority of the major coastal changes occur during high energy storms. The significance of low frequency high energy events is highlighted by both Hewson (1977) and Gerslov (1991) who studied the coastal erosion in South Canterbury.

2.6 Sea level

The current coastal geomorphology and sedimentology is predominantly the product of the Holocene sea level rise. Global sea level became stable around the present level approximately

6,000 years ago, with a relatively minor mid-Holocene highstand around 4,000 years before present (BP) (Pirazolli, 1996; Sloss, Murray-Wallace, & Jones, 2007). It must be noted that sea levels vary significantly regionally and locally (Gibb, 1986; Lewis, Sloss, Murray-Wallace, Woodroffe, & Smithers, 2013; Woodroffe, 2003). Factors that complicate the defining of the eustatic sea level include undulations in the sea surface topography, geoidal humps and troughs, glacio-isostatic effects and varying rates of tectonic tilting, uplift and downdrop, as well as the hemispherical patterns (Gibb, 1986; Isla, 1989). In South Canterbury, rapid sea level rise during the Holocene drowned the coastal lowlands. The sea level reached the present level around 6,000 years B.P (Figure 2.7). Substantial sediment supply from the sea, strong net northwards longshore drift and the rising sea level resulted in rapid and significant change in the coastal geomorphology. It is most likely a spit began to develop at the Wainono Lowland coast around 6,000 years B.P.

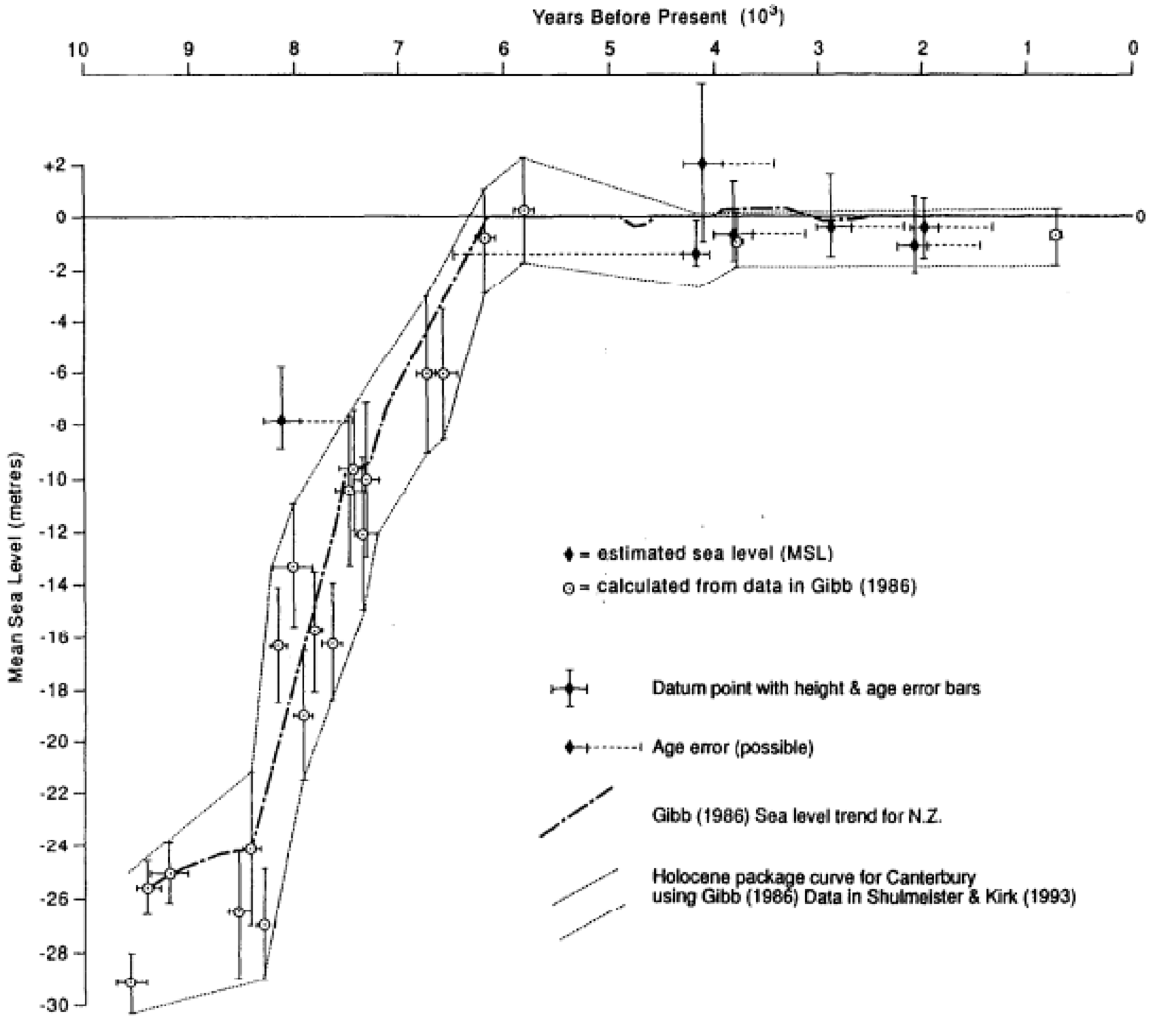


Figure 2.7. Relative sea level curve for the Canterbury region. (Source: Soons et al., 1997, P. 83).

Today, sea levels continue to change all over the world. According to the Intergovernmental Panel on Climate Change (IPCC) the estimated average rate of eustatic sea level rise in the 20th century was between 1 and 2 mm per year. Many regions face the issue of accelerated sea level rise associated with the green house effects and climate change. In New Zealand, the Ministry for the Environment (2009) reported that the relative sea level has risen at an average rate of 1.6 mm per year over the 20th century (Hannah, 2004) (Figure 2.8). Based on the projected future sea level rise produced by IPCC (2007), the Ministry for the Environment (2009) recommends for New Zealand that a base value sea level rise of 0.5 m relative to the 1980 - 1999 average, as well

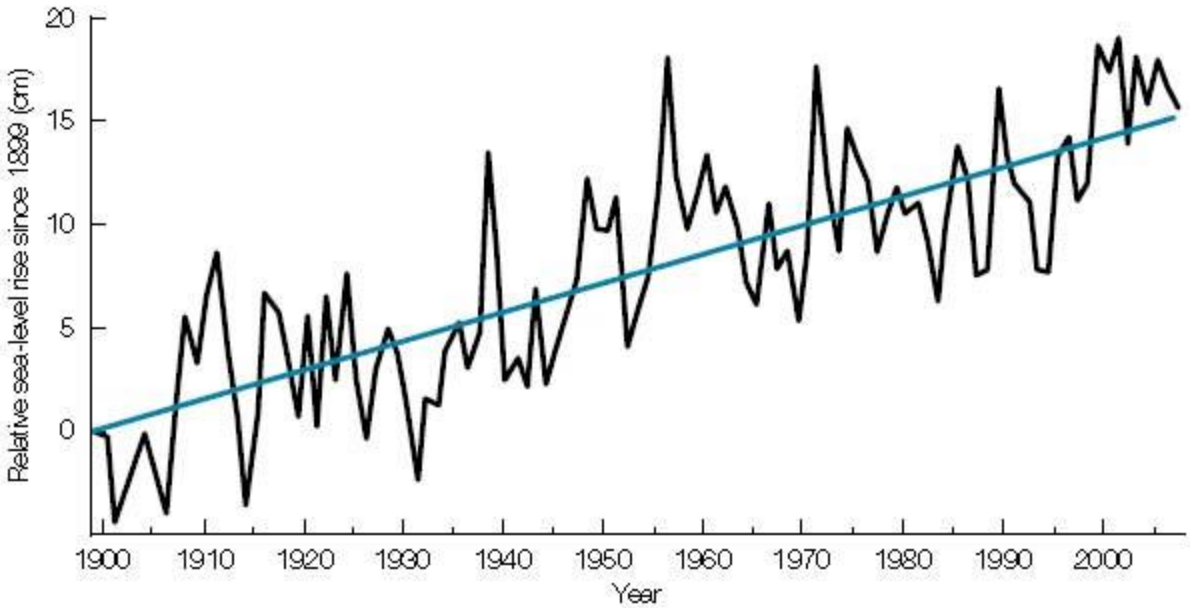


Figure 2.8. Annual mean sea level data from the Port of Auckland, Waitemata Harbour, with a trend line for the period 1899 to 2007. (Source: Ministry for the Environment, 2009)

as an assessment of potential consequences from a range of possible higher sea level rise with a minimum value of 0.8 m, be used for planning and decision timeframes out to the 2090's.

2.7 Water quality

The water quality in Wainono lagoon has degraded over time and become hypertrophic in the recent years. Since 2011, typical plankton during the hypertrophic phase included green algae, diatoms, dinoflagellates and cyanobacteria. The current state of Wainono Lagoon is characterised by high nutrient level, particularly Nitrogen (N) and Phosphorus (P), with high algae biomass. The turbidity is highly variable (recorded range <50 to 1,400 NTU in one day) (Sutherland & Norton, 2011, p. 16). The water clarity is particularly low during prevailing winds which cause resuspension of the fine mud particles. Sutherland and Norton (2011, p. 21) described the water colour as “a translucent green colour (32.5 Munsell Units) during calm conditions” and “a turbid coffee colour (20 Munsell Units) when fully mixed”.

The salinity of the lagoon is also highly variable. It ranges from 5% to 25%, based on the 2009-2011 monitoring period. An increase in salinity is predominantly caused by storm surge, overwash and barrier breach (Sutherland & Norton, 2011).

2.8 Flora and fauna

Wainono Lagoon and the surrounding wetland provide habitats for both native and introduced birds, fish and plant species. In the Wainono-Waihao catchment, 18 native and 8 introduced fish species have been identified. 7 out of the 18 native species are considered to be endangered species, which include Canterbury mudfish (*Neochanna burrowsius*), longfin eel (*Anguilla dieffenbachii*), torrentfish (*Cheimarrichthys fosteri*), giant kokopu (*Galaxias argenteus*), inanga (*galaxias*), lamprey and bluegill bully (Allibone et al., 2010). In terms of birds, 132 species have been identified in the Wainono-Waihao catchment, in which 57 species have been found at Wainono Lagoon. The endemic species include grey duck, black swan (*Cygnus atratus*), and paradise shelduck (*Tadorna variegata*). Introduced species are also seen such as Canada goose (*Branta canadensis*) and mallard (*Anas platyrhynchos*) (Benn, 2011). Typical native plants seen in the river channels and riparian areas of the Wainono-Waihao catchment include *Myriophyllum sp*., *Lilaeopsis novaezelandiae*, horse-mane weed (*Ruppia megacarpa*), *Ranunculus sp*., spike rush (*Eleochonis acuta*), saltmarsh-ribbonwood (*Plagianthus divaricatus*) and flax/harakeke (*Phormium tenax*). Introduced species, algae and periphyton have also been also recorded (Norton, Floeder, & Drake, 2007).

2.9 Historical and cultural significance

Wainono Lagoon was known as *Te Kai Hinaki o Rakihouia* (the food basket of Rakihouia) by tangata whenua (indigenous peoples of New Zealand). The food supply from the lagoon and the ocean was abundant which meant that high spiritual status/power (*mana*) was maintained for the local tribe/sub-tribe. The area was used for fishing, bird hunting and gathering of weaving materials as well as duck eggs. Some areas are still used by the local *whānau* (family) as *mahinga kai* today.

Since 1999, 20 *wāhi tapu* (sacred places) and *wāhi taonga* (sites of significance) have been identified in the Waihao-Wainono catchment by Ngāi Tahu. These places of significance include cultural values listed as below.

- Ara tawhito (ancient trails)
- Umu ti (earth ovens associated with preparation of kauru)
- Kaika Nohoanga (settlement sites)
- Ikoa Tawhito (place names)
- Mahinga Kai (places where resources including food were/are procured)
- Wāhi kaitiaki (resource indicators from the environment)
- Mauka (important Mountains)
- Wāhi kohatu (rock formations)
- Pā Tawhito (ancient pā sites)
- Wāhi paripari (cliff areas)
- Tauranga Waka (canoe mooring sites)
- Wāhi raranga (sources of weaving material)
- Tuahu (sites of significance to identity)
- Wāhi taonga (treasured areas generally)
- Urupā (human burial sites)
- Wāhi tohu (locators and their names within the landscape)
- Repo Raupo (wetlands and swamps)
- Wai Maori (important freshwater areas)
- Wai tapu (scared waters)
- Taniwha
- Reserves, easements, entitlements

Place names and histories also provide cultural background. It is highly important for *tangata whenua* to maintain the connection to land and places as the connection is a significant part of their identity. There are three fishing reserves near Wainono Lagoon, Waikawa (area south of Waihao River mouth), Puhakati/Pukatahi (small area north of Wainono Lagoon), and Te Houriri (a small lagoon between Waihao River mouth and Wainono Lagoon), that were established by the Native Land Court at Ngāi Tahu's request in 1968. These easements ensure the ongoing access of the local *whānau* to *mahinga kai* (Hicks & Todd, 2003; Tipa and Associates, 2012).

2.10 Anthropogenic influences

Most of the coastal lagoons, if not all, have faced impacts from anthropogenic activities that took place in their catchments and/or from management interventions within the lagoon systems. Many of the coastal lagoons in New Zealand have been subject to artificial openings to the sea, by machinery in recent decades and/or by hand by Māori in the pre-European times (Atkinson, 1994). Today, water levels of most waituna-type lagoons are artificially controlled by direct excavation or fixed structures.

In the New Zealand context, the mid-19th century, the arrival of the Europeans, is a benchmark in terms of major changes in the land-use. This has implications to the water quality and sedimentation in the lagoons. Schallenberg et al. (2012), for example, found that the sediment accumulation rates in Lake Waihola, South Island of New Zealand, have increased by 30 times since 1860, which is thought to be linked with the vegetation clearance and extensive agricultural land use since the arrival of the Europeans.

In the Wainono area, it is recorded that extensive wetlands and swamps existed in the area between Willowbridge and the Makikihi River (approximately 14 km along the coast) when the European settlers arrived (Studholme, 1940). It was noted by an early European settler in 1844 that significant numbers of Māori settlements were present in the Waimate and Wainono Lagoon areas. Alteration in land-use, in the catchment area of Wainono Lagoon, began in the mid-19th century. The vegetation was removed and wetlands were drained for agricultural development. Significant tussock fires and bush fires were reported in 1859 (Buller, 1898) and 1878 (Studholme, 1940). Schallenberg and Saulnier-Talbot (2014) argue that this history was evident in the form of charcoal particles in the sandy layer of their sediment core retrieved from Wainono Lagoon. Following the vegetation clearance, draining of the wetlands in the Wainono area began in the 1890s. Numbers of drains were constructed as well as the original Waihao Box which was later destroyed and reconstructed in 1910. Schallenberg and Saulnier-Talbot (2014) also state that the construction of the fixed outlet to the sea introduced salinity to Wainono

Lagoon. This is contrary to the statement of Sutherland and Norton (2011) that salinity is mainly introduced by storm surges, overwashing and barrier breaching. This research supports the view that salinity in the lagoon has naturally fluctuated with changes in barrier morphology and high energy marine forces. The construction of the Waihao Box and farm drains undoubtedly decreased the lagoon size and water level. Today, the Waihao Box is still considered as an important mechanism to control the water level. It requires a repair at regular intervals as it becomes buried under the beach material over time.

Vegetation clearance, lowering of the lagoon level and intensification of agricultural land-use have had significant impacts on the water quality and ecology at Wainono Lagoon. Figure 2.9 illustrates a summary of the environmental history of Wainono Lagoon associated with changes in land-use in the catchment. The lagoon bed gradually shifted from macrophytes to more algae dominated environment. Water levels, sediment accumulation rate and nutrient input have been the key drivers of this environmental change (Schallenberg & Saulnier-Talbot, 2014).

Another important component which can affect the lagoon hydrology is irrigation. As discussed earlier, it is very likely irrigation schemes in the district have influenced the hydrology in the study area. An introduction of irrigation could lead to higher level of groundwater and associated surface water. The Redcliffs irrigation scheme was established in 1936 followed by the Morven Glenavy irrigation scheme in mid to late-1970s. These schemes now operate as Morven Glenavy Ikawai irrigation scheme since 1985, which supplies 18,000 ha of irrigated land. The irrigation races extend to the area 3 km south of Wainono Lagoon. This means that irrigation could result in higher water level in the Dead Arm and Wainono Lagoon.

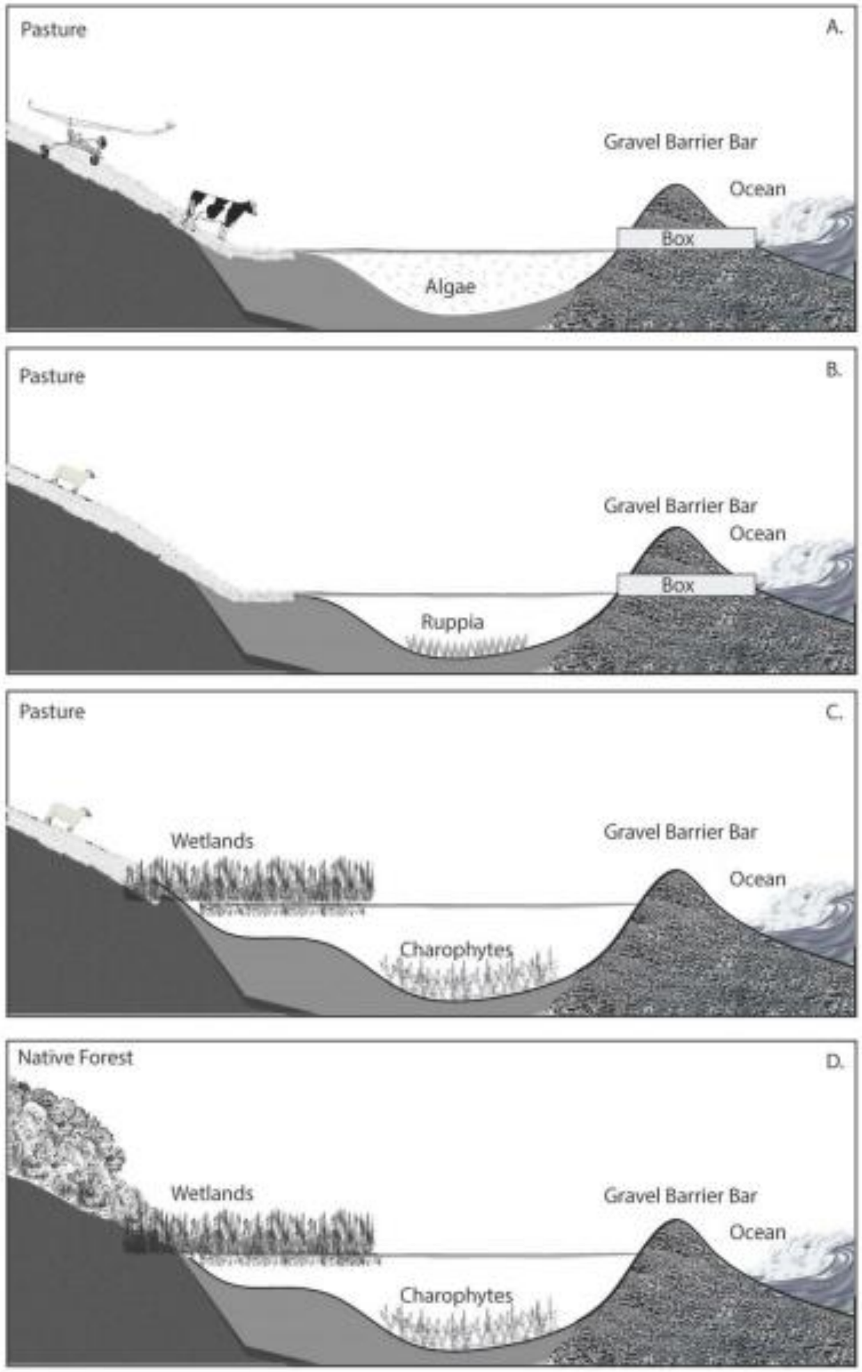


Figure 2.9. A schematic diagram of summarized environmental history of Wainono Lagoon. A: 1960 onwards, B: 1910 - 1960, C: 1850 - 1910 and D: pre-European times in the 1850s. (Source: Schallenberg & Saulnier-Talbot, 2014, p. 27) Note: the Waihao Box is not located at the lagoon barrier but at the Waihao River mouth.

2.11 Summary

The geomorphology of the Wainono Lowland coast is primarily a product of Holocene sea level rise and sediment delivery via longshore drift and the Waitaki River. The Wainono Lagoon system has had significant impacts, from anthropogenic activities, which include the reduced coastal sediment input, reduction in lagoon and wetland area, degradation of water quality by increased nutrient input and accelerated sedimentation in the lagoon. It is reasonable to conclude that expansion of agricultural land-use has resulted in significant changes in hydrology, morphology and ecosystems of the Wainono Lagoon system. The vulnerability of waituna-type lagoons to human-induced environmental changes can not be underestimated. The long-term stability is affected by not only the lagoon catchment but also the source of marine sediment and management of water levels through artificial means. This highlights the importance of holistic approach in lagoon management. Also, what this chapter does not cover is the natural changes in lagoon morphology prior to the arrival of the Europeans. The evolutionary history of Wainono Lagoon remains poorly understood.

Chapter 3. Methodology

3.1 Introduction

In this study, the behaviour of Wainono Lagoon over historical time was investigated in order to answer the research questions stated in Chapter 1. This chapter explains how a multi-technique approach was used to investigate the recent changes in geomorphology as well as to reconstruct the evolutionary and environmental history of the lagoon. Figure 3.1 summarises the methodological approach employed in this research. To assess changes in recent geomorphology at decadal scales, successions of spatial survey data were collected and analysed, as detailed in Figure 3.1a. The evolutionary and environmental history of Wainono Lagoon over longer time scales was reconstructed using a series of sediment core analyses (Figure 3.1b). Results were interpreted together to infer the lagoon morphologies, environments and events of the past. This chapter provides explanations and details of each method employed in this research.

3.2 Recent changes in geomorphology

To examine the geomorphological changes at Wainono Lagoon over recent decades, bathymetric survey data, beach profile data and aerial photographs were collected. Repeated spatial surveys are useful for analysing both spatial and temporal variations. Therefore comparisons between the recent and long-term environmental changes enable an assessment of human impacts on the lagoon system and its geomorphology. This component of the research is directly relevant to the management of Wainono Lagoon, particularly in terms of sediment accumulation information.

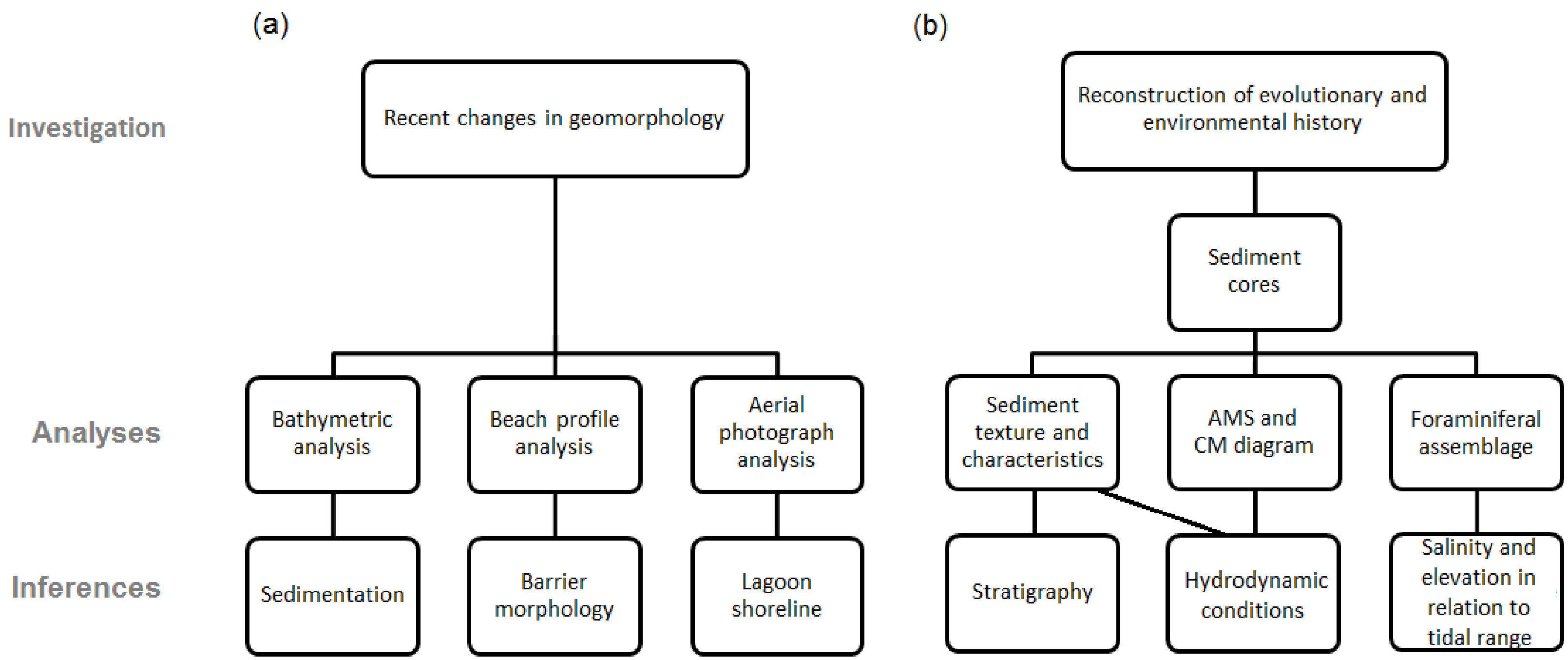


Figure 3.1. Schematic configuration of methodological approach.

3.2.1 Bathymetric survey

This study compared a past bathymetric survey (2002) to the one conducted during the present study (2015). The first accurate bathymetric survey of Wainono Lagoon was conducted by Duncan, Willsman & Shanker in 2002 at Wainono Lagoon, using a Tritech altimeter from a Stabicraft and a Trimble model 5700 Real Time Kinematic (RTK) global positioning system (GPS).

The present study's bathymetric survey was conducted on 28 July 2015. A remote controlled boat, a Tritech PA500 echo sounder and a Trimble model R8 RTK global navigation satellite system (GNSS) were used (Figure 3.3), with the Trimble base station set up on the western side of the lagoon. Measurements of water depth and position were taken at 10 hertz intervals. The GPS was calibrated with positions of ECAN bench marks at IR75 and SCS5513E000 and LINZ marks at ACGF UU 60 and EBJP IT III DP 6769. The position was also checked at SCS5239E036.8. The accuracy was to within ± 10 mm vertically. The weather was fine and calm during the day with thick cloud and thunder developing in the afternoon with a moderate southerly wind. The locations of the survey tracks and of the base station are displayed in Figure 3.2. The data were processed with Trimble HYDRO-Pro software and a contour map and Digital Elevation Model (DEM) was created using *ArcGIS*. The details of the 2002 and 2015 surveys are summarised in Table 3.1.

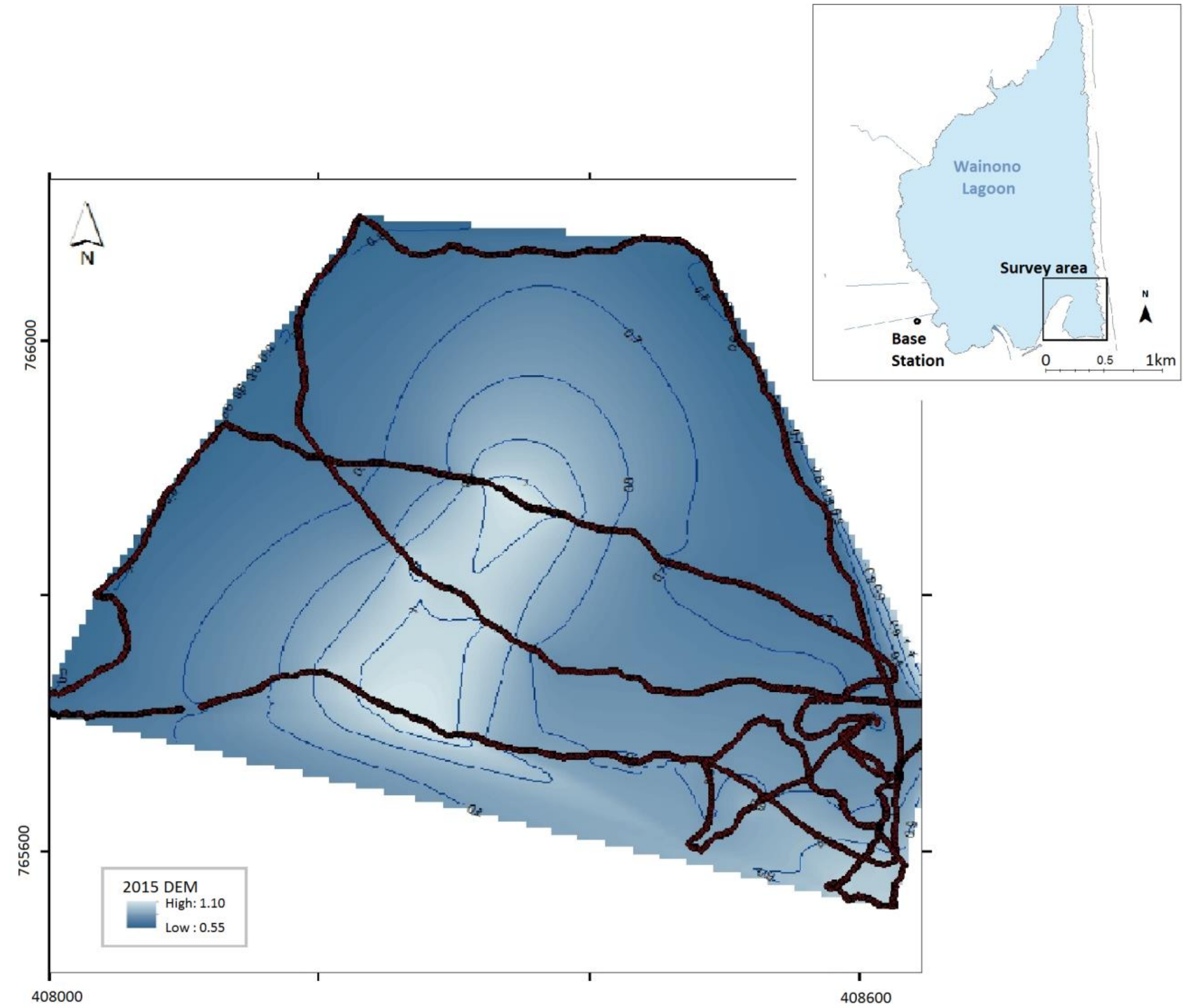


Figure 3.2. The survey path 2015.

Table 3.1. Benchmark adjustment details for 2002 and 2015 bathymetric surveys of Wainono Lagoon. Note: all elevation marks in Canterbury were relevelled in 2013 (mathematical adjustments applied to benchmarks in South Canterbury).

	No. of benchmarks used for calibration	Position	Elevation	Elevation difference measured against ECAN benchmark(s)
2002 Survey	6 LINZ benchmarks	Timaru local circuit GD1949	Lyttelton vertical datum 1937	range - 7 to + 39 mm
2015 Survey	2 LINZ and 2 ECAN benchmarks	Timaru local circuit GD2000	Lyttelton vertical datum 1937	± < 10 mm

Limitations and errors

There are two factors which potentially cause errors. First, the accuracy of positioning has increased as the numbers of satellites available for the GNSS survey have increased between 2002 and 2015. The difference in accuracy can potentially cause errors. The second factor is potential errors deriving from conversion between datum and mathematical adjustments. The 2002 and 2015 surveys employed Timaru local circuit GD1949 and GD2000 datum respectively. The benchmark elevations in South Canterbury were mathematically adjusted in 2013. These factors potentially caused errors, as discussed in the next section.

The 2015 survey area was limited by the range of the remote control boat and capacity of its battery. For unknown reason, the RTK signal was also problematic at the beginning. The RTK issue was finally resolved by directly recording the data from Trimble instead of receiving the data remotely by radio. We only used the data that were reliable and this posed a significant limitation on the survey area.

The contour map and DEM was created by data interpolation. This means that the contours and elevations between survey points are estimated which may differ from reality. Nevertheless, the error caused by interpolation is considered insignificant, particularly for the southern half of the survey area where sufficient measurements were recorded to ensure accurate interpolation. The survey paths are shown in Figure 3.2. Comparison of the 2002 and 2015 surveys embodies errors caused by adjusted benchmark elevations as well as variation in accuracy and in the geodetic datum.

Figure 3.3. Department of Geography remote controlled jet boat with RTK GNSS equipment.

3.2.2 Barrier profile analysis

Temporal variability in beach profile was examined for the period 1985 to 2014. This research focused on the changes in barrier morphology and impacts of high energy events. Spatial variability in beach profile and volume on the Waihao-Wainono Barrier was studied by Stapleton (2005) using ECAN barrier profile data for the period 1985 to 2004. Data for three cross sections (SCS5164 Wainono Hut, SCS5214 Wainono Lagoon and SCS5239 Wainono South) are available along the Wainono barrier as shown in Figure 3.4. Records for the period 1985 to 2014 were obtained from the Environment Canterbury Regional Council (ECAN).

Limitations and errors

One key limitation is that the beach profile analysis is limited to the southern end of the Wainono barrier since records exist for this area only along Wainono Lagoon. This is the most dynamic section of the barrier, with occasional barrier breaches. From 2002, the frequency of surveys was reduced from twice a year to once per year typically in October. Therefore seasonal changes since 2002 are unknown.

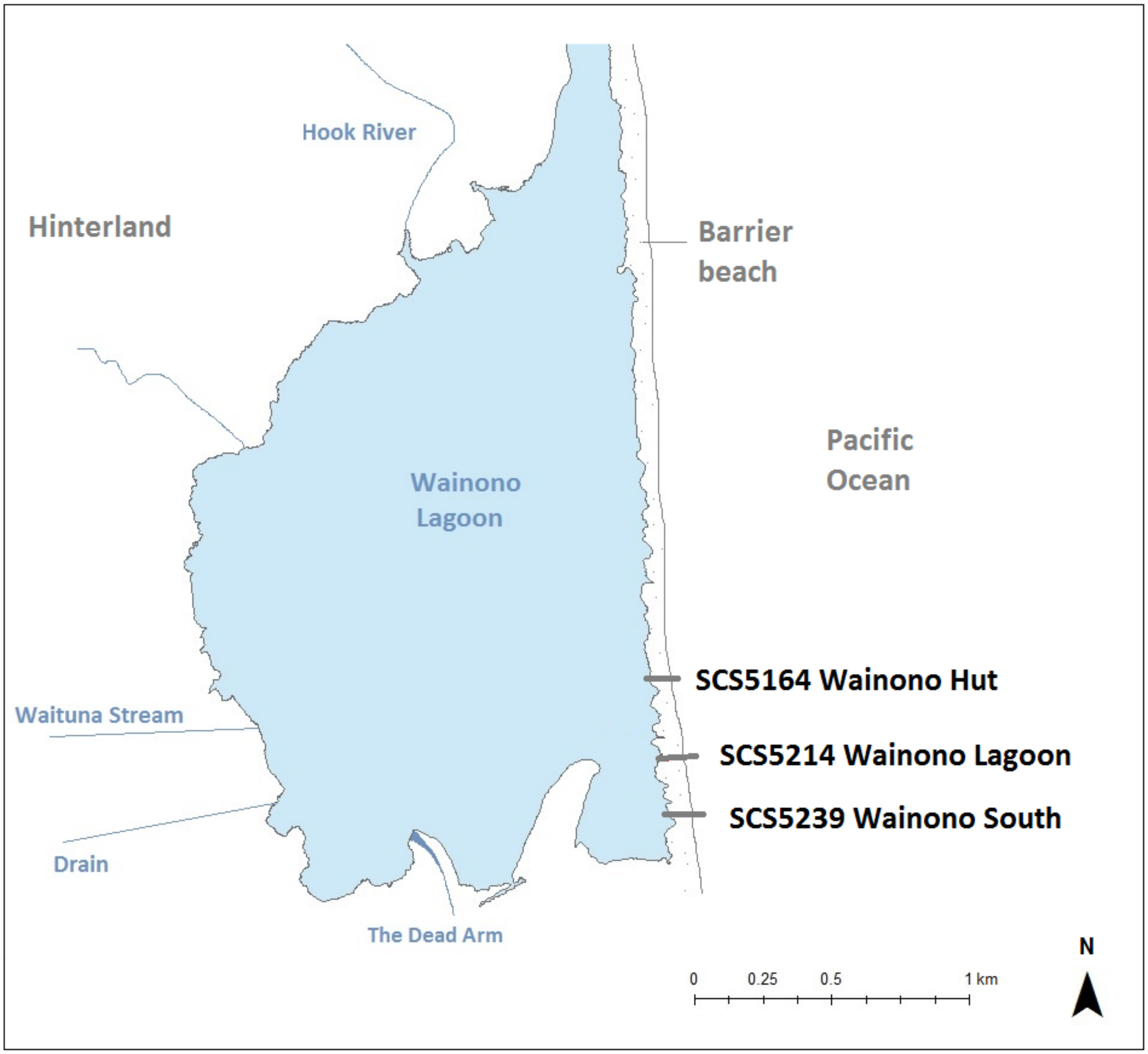


Figure 3.4. Location of Ecan cross sections on Wainono barrier.

3.2.3 Aerial photograph analysis

A series of aerial photographs were collected in order to assess changes in the position of both lagoonal and coastal shoreline. Aerial photographs taken in February 1969 (SN2139, Photo ID 8), March 1977 (SN5068, D), February 1984 (SN11049, L) and January 1992 (SN12210, K) were obtained from ECAN. An aerial photograph taken in November 2009 was also obtained from Kiwiimage CA19. The photographs were geo-referenced with four control points and the lagoon edge was digitised using *ArcGIS*. The wet line on the beach was also digitised to assess the changes in the position of the coastline. The images were superimposed to allow visual assessment. The lagoon area in each image was also calculated to assess changes in the lagoon size over time. The resolution of the 1969 photograph was too low and significantly distorted therefore was not used for this analysis.

Limitation and errors

Errors can be associated with the resolution, distortion and human error during the geo-referencing and digitising processes. Human error in particular is not quantifiable. The analysis is primarily used to study the general trends. The timeframe used for the analysis is also limited by availability of aerial photographs and their suitability for digitisation.

It is challenging to establish a trend based on limited data due to the variables influencing the wetted perimeter. The position of the lagoon shoreline varies depending on the water level which is governed by the balance between the inflow and outflow. The wet line on the beach, which was used to digitise the coastline, represents the limit of water at the time of aerial image being taken and is largely influenced by the tide. The wetted perimeter in the lagoon is also affected by weather, tide and connection to the sea. The tide and water levels at the time of aerial images being taken are unknown. This issue will be discussed further in Chapter 6. Table 3.2 shows the average daily mean flow data at Waihao McCulloughs (approximately 15 km southeast of Wainono Lagoon) for the same month, plus the past three months, as when the aerial images used in this study were taken. The three month average flow data for the period 1984, 1992 and 2009 do not significantly vary and it is assumed the inflow to Wainono Lagoon during these months present a similar pattern. It can be argued that January to February 1984 and November 2009 was relatively dry. A longer time frame is required to establish a more comprehensive trend in shoreline changes.

Table 3.2. Average daily mean flow at Waihao McCulloughs, Waimate (Data from Environment Canterbury). Note: Continuous flow data for the period 1984 to 2009 were only available for the Waihao McCulloughs site.

Month	Monthly average (m^3/s)	Three month average (m^3/s)
Jan - Mar 77	N/A	N/A
Dec-83	5.791	
Jan-84	1.239	
Feb-84	0.706	2.579
Nov-91	2.423	
Dec-91	2.575	
Jan-92	2.517	2.505
Sep-09	4.061	
Oct-09	2.922	
Nov-09	0.875	2.619

3.3 Reconstruction of evolutionary and environmental history

Several techniques were used to reconstruct the evolutionary and environmental history of Wainono Lagoon. Sediment cores obtained from the bed of Wainono Lagoon were used to establish the stratigraphy and for analyses of AMS, grain size and foraminifera. Inferences of historical events and environments were made based on an examination of the complete set of core analyses data together.

3.3.1 Sediment cores

Sediment cores were retrieved using a piston corer on 15 June 2015. The weather condition was calm and fine. No waves were present and the water depth was approximately 800 mm at the coring sites. Samples WLB1 and WLB2 were collected 1 m apart at map reference S44°42’34.9 E171°09’58.2 (marked as WLB in Table 3.3). Samples WLW1 and WLW2 were collected 1 m apart at map reference S44°42’36.0 E171°08’53.8 (marked as WLW in Figure 3.5). The North orientation was marked on all plastic core collection tubes at the beginning of each coring process. The sample details of cores retrieved are summarised in Table 1.3.1.

Table 3.3. Details of sediment core samples retrieved from Wainono Lagoon.

Sample	Diameter (mm)	Length (mm)	Catcher
WLB 1	47	770	Butterfly valve
WLB 2	47	970	Butterfly valve
WLW1	35	1030	Plastic core catcher
WLW2	47	760	Butterfly valve

The external sediment core tube casings were split vertically using a table saw at the UC Geography Department laboratory and then the sediments were split using a metal wire. Small sections of sediment were sampled for each analysis.

Limitations and errors

A limitation was posed on the length of cores. A vibro-corer retrieves a longer core compared to the piston corer which was employed in this study. However a vibro-corer disturbs the orientation of sediment grains during the coring process and therefore is not suitable for AMS analysis. Also the maximum length was limited to the length of the tubes available, which was approximately 1.2 m.

Compaction of sediments is expected to have occurred during the coring process. The degree of compaction may differ between two different valves that were used. Core WLW1 was retrieved using a different type of valve while cores WLB1, WLB2 and WLW2 were retrieved using the same valve.

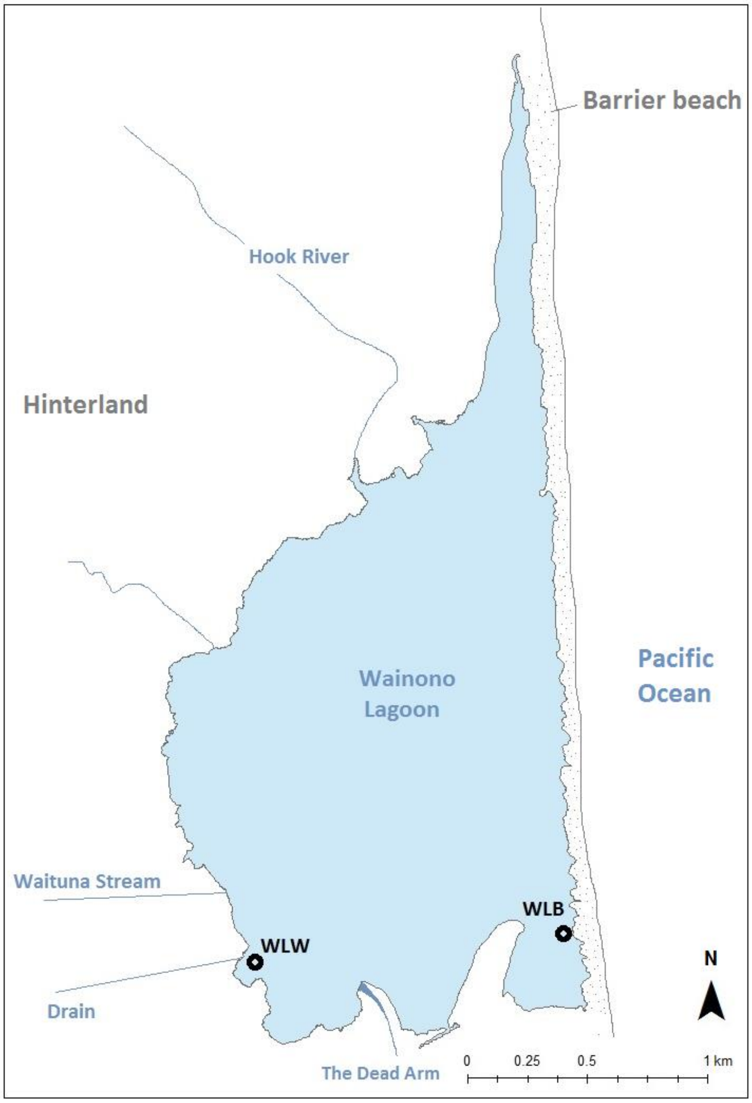


Figure 3.5. Locations of coring sites WLW and WLB in Wainono Lagoon. WLW is short for Wainono Lagoon West and WLB is short for Wainono Lagoon Barrier.

3.3.2 Sediment core analysis

Visual description of sediment was conducted immediately after the cores were split in the laboratory. Sections of differing sediment characteristics were visually identified. For each section, the depth and sediment colour was recorded using Munsell Soil-Color Charts, sediment texture was described and a core log was developed of the units found in the core. This analysis was used to describe the core and determine the sample locations for other analyses.

Limitations and errors

The visual sediment core analysis alone does not present accurate characteristics of sediments. However it is useful when used in conjunction with other analyses such as grain size and AMS.

3.3.3 Anisotropy of Magnetic Susceptibility

Anisotropy of Magnetic Susceptibility (AMS) was analysed to infer the hydrodynamic conditions including flow directions and energy environments that existed during the settling phase of the sediments. AMS has been widely used in geological and geophysical research to investigate and depict the preferred orientation of magnetic minerals in rock (e.g. Borradaile, Genviciene, & Charpentier, 2012; Dubey, 2014) or unconsolidated sediments (e.g. Kain et al., 2014; Liut et al., 2005; Wassmer & Gomez, 2011; Wassmer, Gomez, Iskandarsyah, Lavigne, & Sartohadi, 2015; Wassmer et al., 2010).

When a sediment sample is exposed to a magnetic field (H), it exhibits an induced magnetic moment (M). H is proportionate to M, linked by the magnetic susceptibility (k), according to the following relationship;

$M = kH$.

M and H are measured in amperes per meter ($A \cdot m^{-1}$), whereas k is a dimensionless quantity.

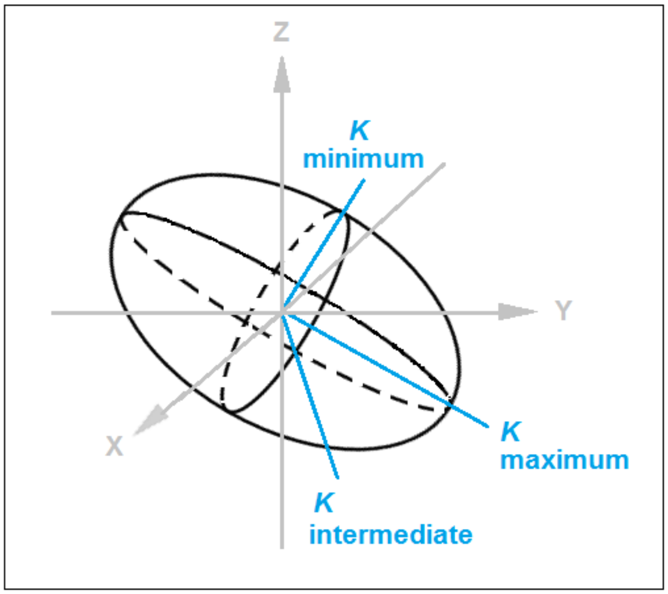


Figure 3.6, The electromagnetic ellipsoid showing the maximum, minimum and intermediate axes.

The AMS technique measures the orientation of the magnetic ellipsoid (Figure 3.6) that occurs when a sample is exposed to a magnetic field (H). Sediment samples are characterised by their anisotropy of magnetic susceptibility, which can be visualised as a triaxial AMS ellipsoid with eigenvectors: K1, K2, K3 representing the maximum, intermediate and minimum susceptibility axes respectively (Tarling & Hrouda, 1993). The magnitude of the AMS is governed by the anisotropy of the sediment grains and degree of alignment (Dubey, 2014). The maximum susceptibility axis K1 is generally parallel to the mean long axis of the individual grains in sedimentary deposits (Wassmer et al., 2010). In this study, AMS was analysed to investigate the orientation and degree of alignment of sediment grains within the cores, which can be used to infer the hydrodynamic conditions present during the settling phase of the sediments (Rees, 1965).

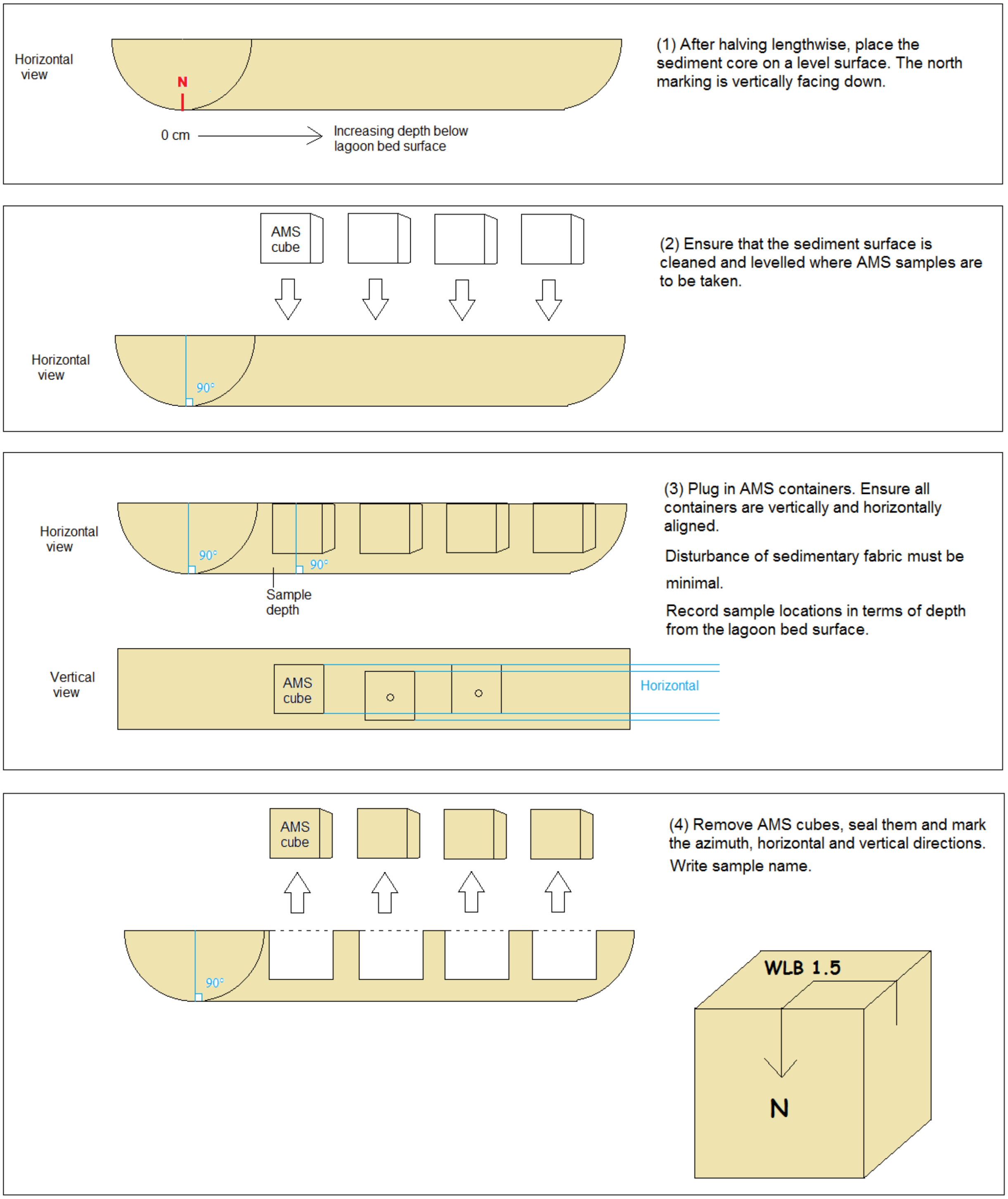


Figure 3.7. Methodology for AMS sampling from cores.

Figure 3.8. Vertical view of the sediment core. AMS sample containers were manually pushed into the cores. Note the small holes on the top of the containers, which allow air to escape, minimizing sediment disturbance.

AMS sampling was carried out as detailed below. Figure 3.7 illustrates the AMS sampling methodology employed in this research.

1. The core tubes were placed with the north mark facing down at a 90° angle while ensuring that the sediment surface was exactly horizontal.
2. Sediment samples were taken by plugging 2 x 2 x 2 cm^3 non-magnetic cubes (clear containers) vertically into the halved cores. A small (1 mm diameter) hole was drilled on each sample container to allow air to escape. This is to avoid disturbance of sediment orientation by pressure during plugging. The cubes were manually pushed into the sediment and the sample locations (depths) were noted (Figure 3.8). Samples were taken from each section identified by visual stratigraphy analysis. 13 samples were retrieved from cores WLB1 and WLB2. 11 samples were retrieved from WLW2.

3. The azimuth, horizontal and vertical directions were marked on each cube. Samples were sealed after removing from the core to avoid desiccation and disturbance of the sedimentary fabric.
4. AMS analysis was carried out by a Kappabridge KLY-2 device which measured each sample from 15 angles to determine the magnitude and direction of the maximum, intermediate and minimum AMS axes/tensors (K1, K2 and K3 respectively) according to the method of Tarling and Hrouda (1993).

Limitations and errors

There are a few factors that potentially created small margins of error. First, the sediment entered the sample tube via a butterfly valve and this can in places cause minor disturbance in the orientation of sediment grains. AMS samples were not taken from areas where sediment disturbance was visually observed. Second, the positioning of the North was marked on the metal sleeve of the corer at the beginning of each coring process in the lagoon. The orientation of the North was marked on the sample tube when it was taken out of the sleeve. The corers and cores were handled very carefully, however, there is a possibility that the tube has moved slightly inside the sleeve during the coring process. Third, air gaps within the cubes can increase error in AMS analyses. Difficulties were experienced while plugging into WLW2 as the sediment was highly cohesive and considerable air gaps were present in WLW2.4, WLW2.8, WLW2.9 and WLW2.10. Errors in WLW2 are not critically important in this research since significant findings based on the AMS analysis rely on cores WLB1 and WLB2. The overall results show a good level of consistency and the data are considered reliable.

The practicality of the AMS analysis was limited by the grain size and thickness of the sediment layer. Fine sediment particles posed physical difficulties in sample collection and potential error in analysis. The top muddy sections of the cores, representing sediment from near the lagoon surface, were not sampled for AMS because the sediments were too cohesive such that the sediment grains moved and changed alignment as a cube was pushed into the sediments. Resuspension and redistribution of fine sediments in shallow lakes and enclosed lagoons (Hamilton & Mitchell, 1996; Sutherland & Norton, 2011) can also be problematic for AMS analysis, causing difficulties in establishment of flow patterns for fine sediment layers (e.g. fine silt and clay). For this reason, the AMS analysis in this research focussed on the sand sediment deposits in cores only. Thin layers less than 2 cm were not sampled as the results would not represent the layer accurately.

3.3.4 Foraminiferal analysis

Foraminiferal assemblages in the sediment samples were analysed to infer the salinity range of the past environments. The presence of certain species in the sediment samples can indicate the salinity and elevation relative to mean sea level of the sediments at their time of deposition. This information is used to examine the degree of marine influence, which support the hydrodynamic information derived from AMS and grain size analyses, to reconstruct the barrier morphology, at the time of the sediment deposition.

Macrofossil analyses are commonly used to infer palaeoenvironmental conditions (e.g. Martins et al., 2014; Soons et al., 1997) (Table 3.4). A diatom analysis was used by Schallenberg and Saulnier-Talbot (2014) to examine sediment cores from Wainono Lagoon. Diatoms were absent/very rare below the depth of 75 cm in their sediment core, which was retrieved from the centre of the lagoon. This research employed a different approach and examined the foraminiferal assemblages to infer the salinity range of past environments. This methodology was used by K. J. Clark et al. (2015) who found historical tsunami deposits in Big Lagoon in Marlborough, New Zealand by establishing marine foraminiferal assemblages in the sediments. The foraminiferal analysis, in conjunction with the AMS and grain size analyses, can be used to reconstruct historical events such as a barrier breach. This methodology is suitable for this research as the changes in barrier morphology are an important component. Table 3.4 shows the summary of benthic foraminiferal distribution in brackish water in New Zealand.

A total of 36 samples from cores WLB1, WLB2 and WLW1 were analysed. A sediment sample was also taken from the core WLB2 nosepiece (Figure 3.9) for foraminiferal analysis. Each subsample material of approximately 12 – 15 cm^3 was wet sieved to remove grains smaller than 63 µm. Samples were placed in glass beakers and oven-dried at 50°C. Dry samples were examined under a microscope. Every foraminifera observed was manually picked up using a wet

Table 3.4. Schematic summary of the distribution of relative abundance of common benthic taxa in brackish water environments in New Zealand. (Modified from Hayward, Grenfell, Reid & Hayward, 1999)

(Freshwater) 1ppt	Salinity	(Marine) 35ppt
Trochamminita salsa		
Miliammina fusca		
Haplophragmoides wilbert		
Ammotium fragile		
Jadammina macrescens		
Trochammina inflata		
Ammobaculites exiguus		
Scherochorella moniliforme		
Textularia earlandi		
Elphidium gunteri		
Elphidium exc. F. excavatum		
Elphidium exc. F. clavatum		
Ammonia parkinsoniana		
Ammonia pustulosa		
Elphidium exc. F. williamsoni		
Haynesina depressula		
Elphidium advenum s.l.		
Bolivina neocompacta		
Spiroloxostoma glabra		
Portatrochammina sorosa		

Abundance > 50% approx.	
Abundance < 50% approx.	

Figure 3.9. Extra sediment preserved in the nosepiece.

brush and the species were identified according to Hayward et al. (1999). The aim was to pick out and identify a target of 100 specimens per sample.

Limitations and errors

Several foraminifera were lost during the picking process. The target of 100 specimens was not met, however, sufficient numbers of foraminifera were found to infer the environment of samples which contained foraminifera. Preservation of foraminifera can pose a limitation. When marine foraminiferal species are brought into a freshwater dominated environment, by a tsunami for example, there is possibility that the dissolution of tests occur due to the change in pH. This implication is discussed further in Chapter 5.

3.3.5 Grain size analysis

Grain size distribution in the sample sediments was measured using a laser sizer. Grain size analysis used in conjunction with the AMS analysis maximises the understanding of sediment transport, deposition and energy environment (Wassmer et al., 2010). In total, 54 samples from cores WLB1, WLB2, WLW1 and WLW2 were analysed using Saturn Laser Digisizer II. Laser diffraction particle sizing produces detailed and highly accurate data that are useful for inferring the past environmental parameters (Blott & Pye, 2006; Jonkers, Prins, Brummer, Konert, & Lougheed, 2009). After completion of the AMS analysis, sediments in the AMS sample containers were used for the grain size analysis. Extra samples were also taken from sections that were not suitable for AMS plugging. A mixture of distilled water and sodium hexametaphosphate was added to each sample and stirred well to break down sediment grains. This was essential because samples contained clay which is highly cohesive. A pipette was used to extract a small sample which was measured by the laser sizer.

Limitations and errors

Two potential limitations are presented here. One key limitation is that the laser sizer does not measure grains larger than 2.5 mm. However, in this research, the majority of the sediment grains were smaller than 2 mm, except for a few materials such as wood pieces. Therefore this limitation should not have affected the results.

Another limitation is on the data presentation. Sieve size data are useful in displaying the sediment characteristics. However, the conversion from the laser diffraction size to sieve size can cause errors. The converted sieve size from the laser size can differ from the actual dry sieve results due to the grain shapes and assumption involved in the calculation of size distribution.

3.3.6 CM diagram

A CM diagram will be used to examine the transport mechanism at the time of the sediment deposition. The use of the CM diagram assists the interpretation of AMS and grain size results and to infer the hydrodynamic condition at the time of the sediment deposition.

A CM diagram exhibits the relationship between the transport condition and grain size parameters (Passega, 1957). Parameters C (an approximation of the maximum grain size) and M (the median) indicated the hydraulic conditions under which sediments were deposited (Passega, 1977). In this study C95 values are used instead of C99 to avoid bias due to the outliers, the values of abnormally coarse grains within the grain-size distribution (Allen, 1971; Wassmer et al., 2010). According to the CM diagram, 'rolling' is the transport mechanism of the coarsest sediments with the highest C95 and median values, which epitomises the highest energy conditions. As energy decreases, the transport is represented by 'gradual suspension' followed by 'uniform suspension'. In the lowest energy condition, sediment transport mechanism is epitomised by 'pelagic suspension' and 'pure suspension'. 'Bed load' for C95 values of > 500 µm occurs beyond the boundary of the CM diagram.

Limitations and errors

Information derived from the CM diagram has limits and needs to be integrated with other evidence on hydrodynamic conditions (Passega, 1977). In this study the CM diagram is used to assist the results of sediment analyses including sediment characteristics and AMS. Mycielska-Dowgiałło and Ludwikowska-Kędzia (2011), who studied the granulometric analyses of Quaternary deposits, found that the CM diagram can be used for both fluvial and marine deposits. This means that the CM diagram is a useful tool for lagoon sediments which may contain both fluvial and marine deposits.

Chapter 4. Recent changes in geomorphology at Wainono Lagoon

4.1 Introduction

Results and interpretation relating to geomorphological changes in the recent decades are presented in this chapter. Results of bathymetric survey, beach profile analysis and aerial photograph analysis are displayed with interpretation. All results are analysed conjointly in summary synthesis at the end of the chapter.

4.2 Lagoon bathymetry

Changes in the bathymetry at Wainono Lagoon were assessed using the bathymetric survey data from 2002 (Duncan et al., 2002) and 2015. Contour maps of the south-east section of Wainono Lagoon have been created using the 2015 and 2002 data (Figure 4.1). The DEM 2015 shows the current bathymetry of the surveyed area. Two cross sections of the lagoon bed (CS1 and CS2 shown in Figure 4.2a) were also examined to analyse the profile changes between 2002 and 2015. The results are displayed in Figure 4.2b-c.

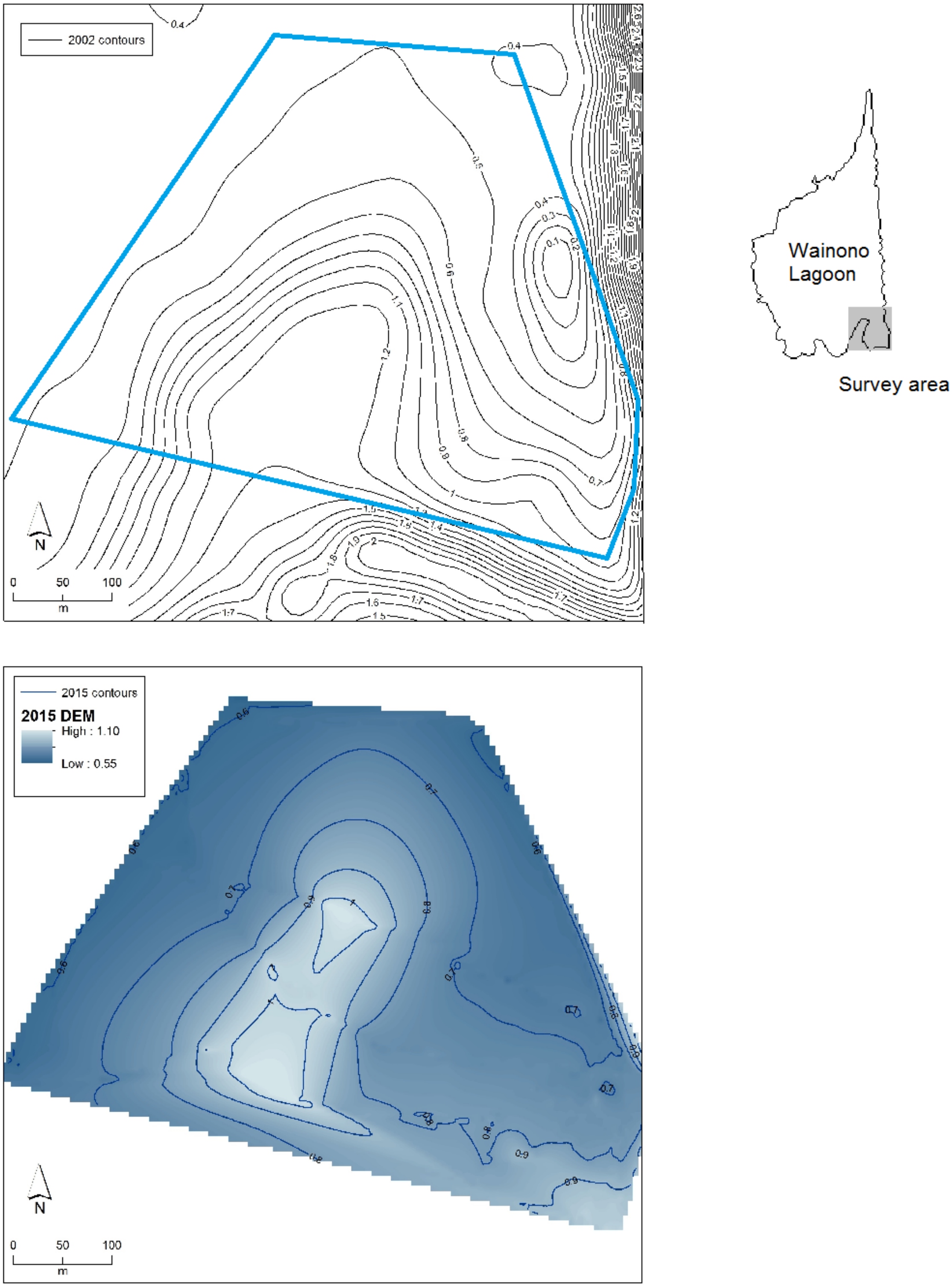


Figure 4.1. Contour maps of the south-east margin of Wainono Lagoon created from the 2002 and 2015 survey data. The 2002 map includes a blue line indicating the extent of the 2015 survey.

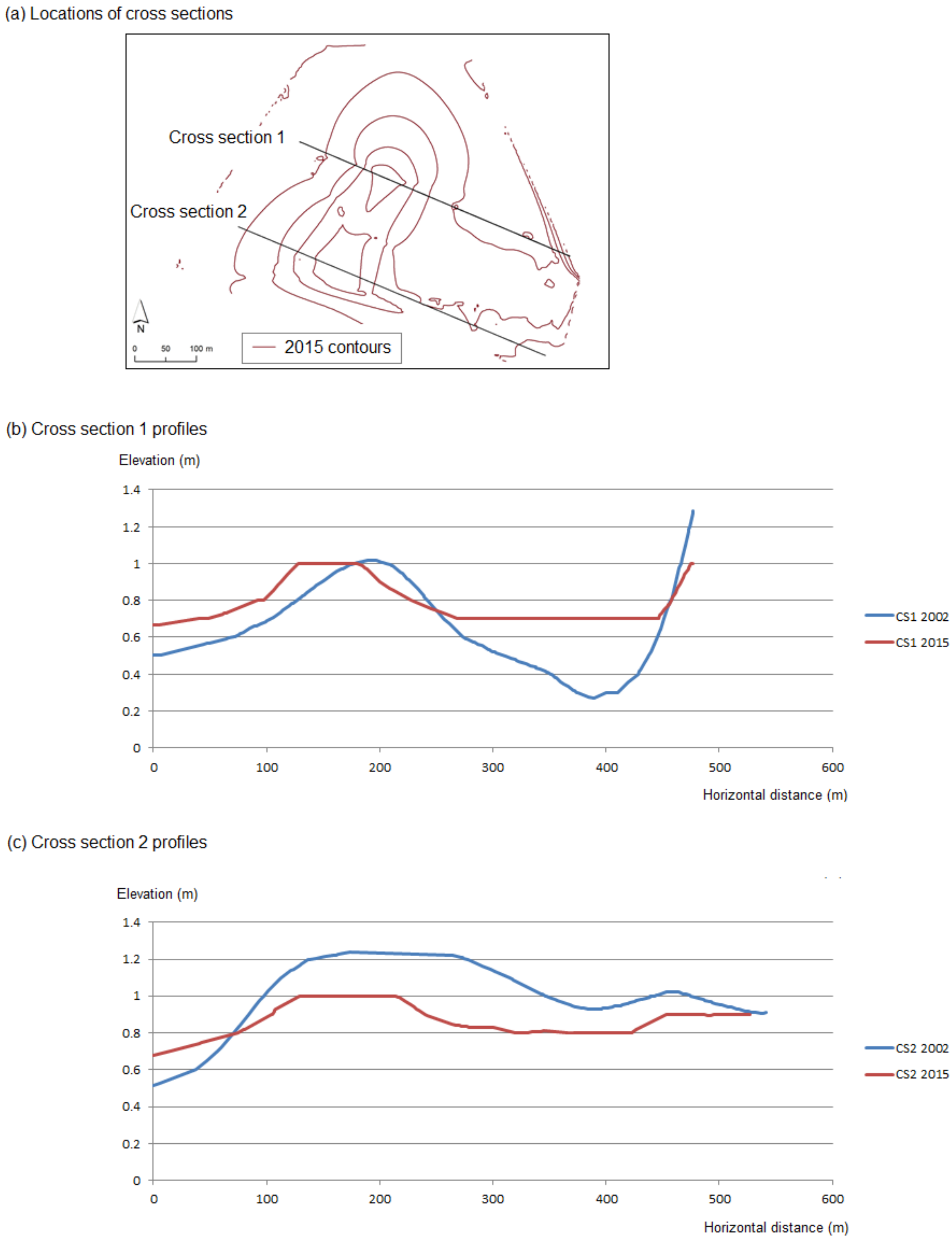


Figure 4.2. (a) Locations of Cross section 1 (CS1) and Cross section 2 (CS2), (b) lagoon cross sectional profiles CS1 2002 and 2015, (c) lagoonal cross sectional profiles CS2 2002 and 2015.

The bathymetric analysis indicates that resuspension and redistribution of sediments occurred in the survey area. CS1 displays an overall increase in the elevation of the lagoon bed whereas CS2 shows an overall decrease. The depression which was present in 2002 in CS1 became filled over time. CS2 shows that the elevated lobe was lowered by approximately 0.23 m during the survey period. The sediment accumulated on the elevated lobe, possibly during high energy events, was redistributed by runoff or resuspension and deposited on other parts of the bed over time.

This analysis is only a snapshot of the bathymetry change temporally and spatially, however, the results show that the spatial variation in sedimentation rates can be significant.

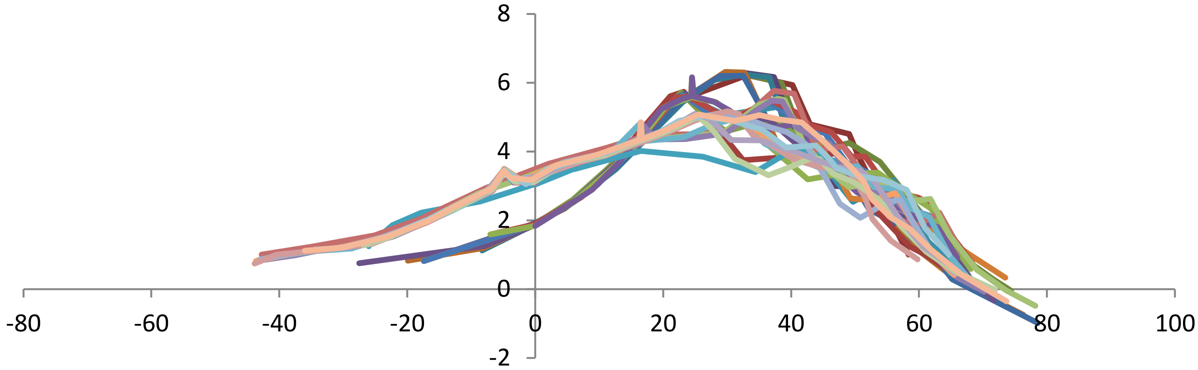
4.3 Beach barrier profile analysis

Changes in beach barrier morphology were analysed using a series of beach profile survey results at survey sites SCS5164 Wainono Hut, SCS5214 Wainono Lagoon and SCS5239 Wainono South over the period 1985 to 2014. Data for 1985, 2002 and 2003 for SCS5164 Wainono Hut and data for the period 2002 - 2004 for SCS5239 Wainono South were not available. The locations of the survey sites were shown in Chapter 3. Figure 4.3 displays the winter-spring barrier profiles over the survey period.

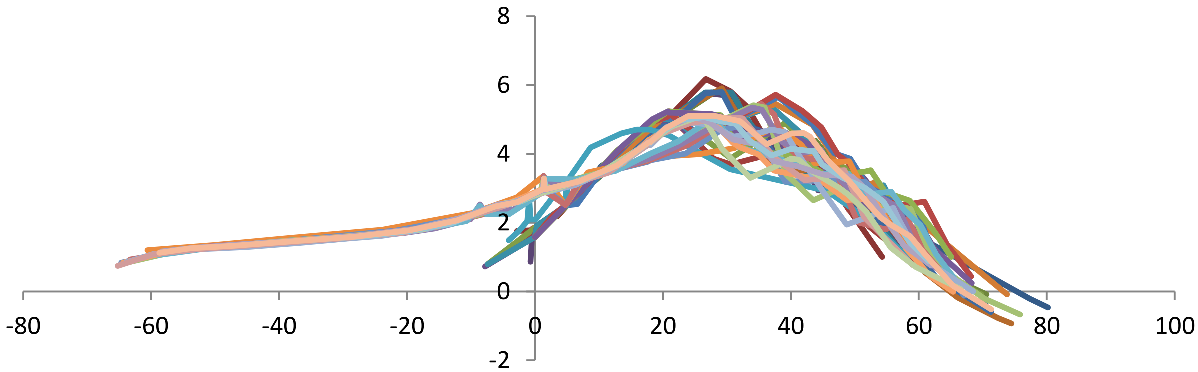
Excursion distances were also analysed and results are displayed in Figure 4.4, which shows the changes in the position of the backbarrier and beach face at 2 m AMSL and changes in the barrier crest height over the period 1985 to 2014.

Figure 4.3 and Figure 4.4 show that the position of the backbarrier at 2 m AMSL at all three sites migrated landward during the survey period. Major changes are evident after the 2001 and 2002 storm events. The barrier crest was lowered and significant washover of beach material was evident on the backbarrier. It was reported that a 1 km stretch of the Wainono barrier was lowered by an average of 1 m during the 2001 storm event (Cope & Young, 2001). Over the survey period, the position of the backbarrier at 2 m AMSL shifted >15 m landward at SCS5164 Wainono Hut and SCS5214 Wainono Lagoon and approximately 10 m landward at SCS5239 Wainono South. In contrast, landward movement of the beach face at 2 m AMSL was either not evident or insignificant. The results show progradation at SCS5164 Wainono Hut (+ 18 mm / year) and SCS5239 Wainono South (+ 289.66 mm / year), and landward retreat at SCS5214

(a)



(b)



(c)

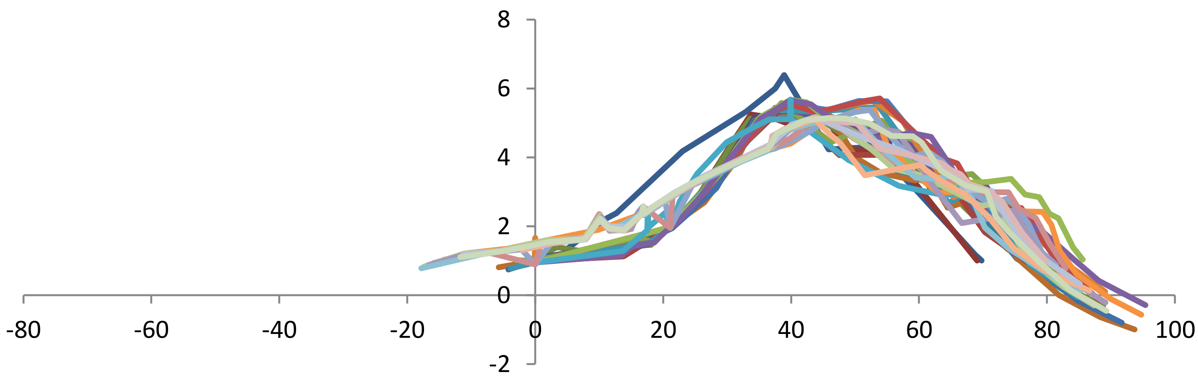


Figure 4.3. Beach barrier profile changes at (a) SCS5164 Wainono Hut 1986 - 2014 (b) SCS5214 Wainono Lagoon 1985 - 2014 (c) SCS5239 Wainono South 1985 - 2014.

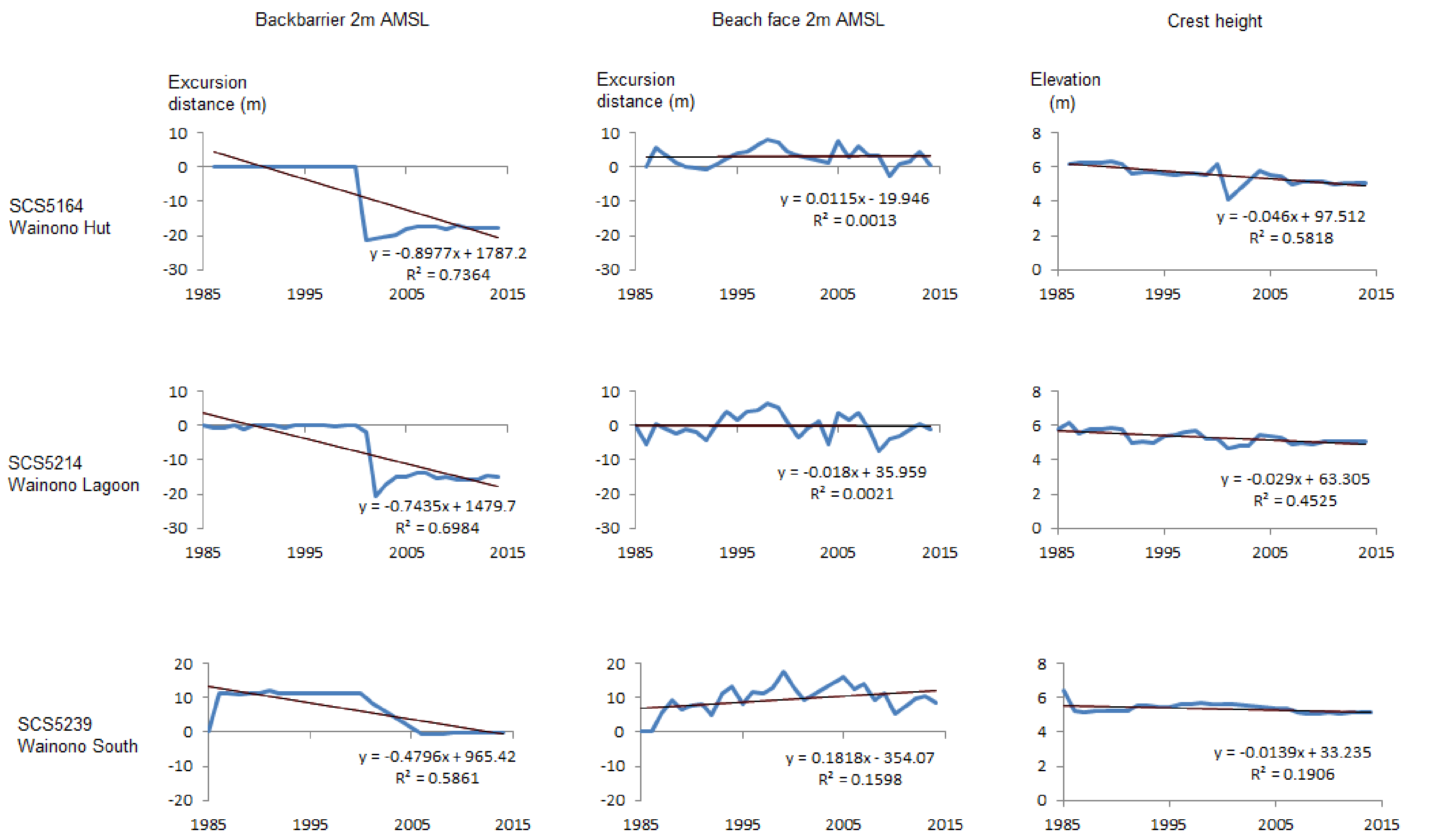


Figure 4.4. Excursion distances for the backbarrier and beach face at 2 m AMSL and for the barrier crest height (blue lines) at survey sites SCS5164 Wainono Hut, SCS5214 Wainono Lagoon and SCS5239 Wainono South with trend lines shown in red.

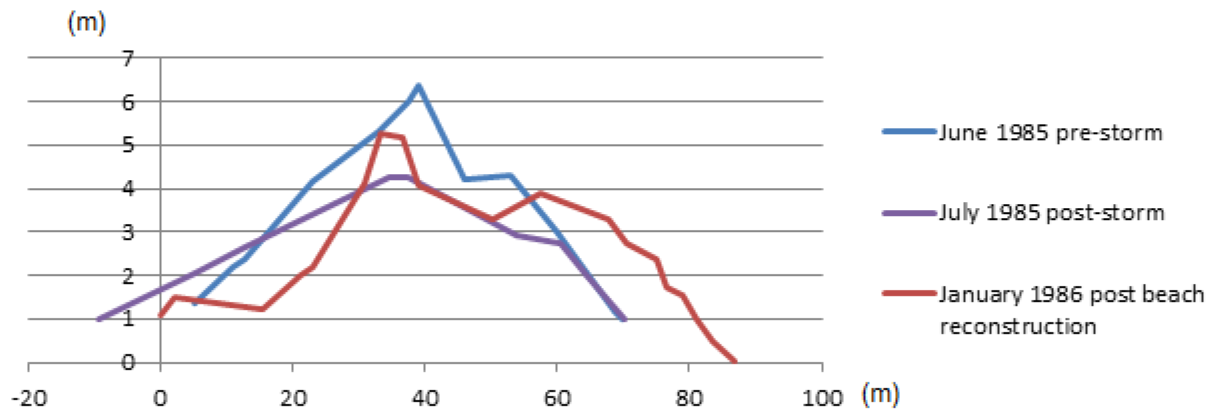


Figure 4.5. Profile changes at SCS5239 Wainono South showing human intervention in post-storm barrier profile.

Wainono Lagoon (- 30 mm / year). The crest heights at all sites show a slight decrease over time. This means that washover of beach materials occurred but, over the survey period from 1985 to 2014, the barrier is not necessarily rolling over. After the storm events in 2001 and 2002, the barrier became wider and flatter. These findings will be discussed further in Chapter 6.

Human intervention is evident in the barrier morphology at SCS5239 Wainono South as shown in Figure 4.5. The comparison of pre-storm and post-storm barrier profiles in 1985 shows a decrease in crest height and landward movement of beach material by overwash. The landward movement of sediment is naturally irreversible unless human intervention is involved (Matias et al., 2012; Single, 1992). The profile in 1986 shows that beach material was moved seaward and the barrier crest was raised. An artificial beach reconstruction was carried out by the South Canterbury Catchment Board after the barrier breach in 1985. No artificial work was carried out at Wainono South after the 2001 and 2002 high energy events (Scarlett, pers.com, 2015).

The barrier profile analysis found evidence of overwash and human intervention. Barrier translation is occurring at SCS5214 Wainono Lagoon Wainono Lagoon, however is not evident at SCS5164 Wainono Hut and SCS5239 Wainono South. This is discussed further in section 6.3.

4.4 Aerial photograph analysis

A series of aerial photographs were collected in order to assess the changes in the position of the lagoonal and coastal shoreline. Of particular interests were changes in the size of the lagoon and whether lagoon retreat is occurring.

Wainono Lagoon aerial images from 1977, 1984, 1992 and 2009 are displayed in Figure 4.6, with overlays of digitised shorelines of the lagoon and beach. The shorelines are superimposed on the 2009 aerial image in Figure 4.7 for visual comparison. Figure 4.7 shows that the coastline in the northern section of the lagoon prograded over the analysis period of 32 years. Conversely in the southern section, the position of the coastline does not show significant changes while the landward movement of the backbarrier was evident. The lagoon shoreline on the landward side was located further to the west in 1977 compared to 1984, 1992 and 2009.

The surface area of the digitised lagoon was calculated and displayed in Table 4.1. The results show fluctuations, but indicate an overall decline in the surface area over the analysis period of 32 years. Based on the data used in this study, Wainono Lagoon shrunk in size by 11% between 1977 and 2009, but this is most likely a trend over a short period of time. This will be discussed in Chapter 6.

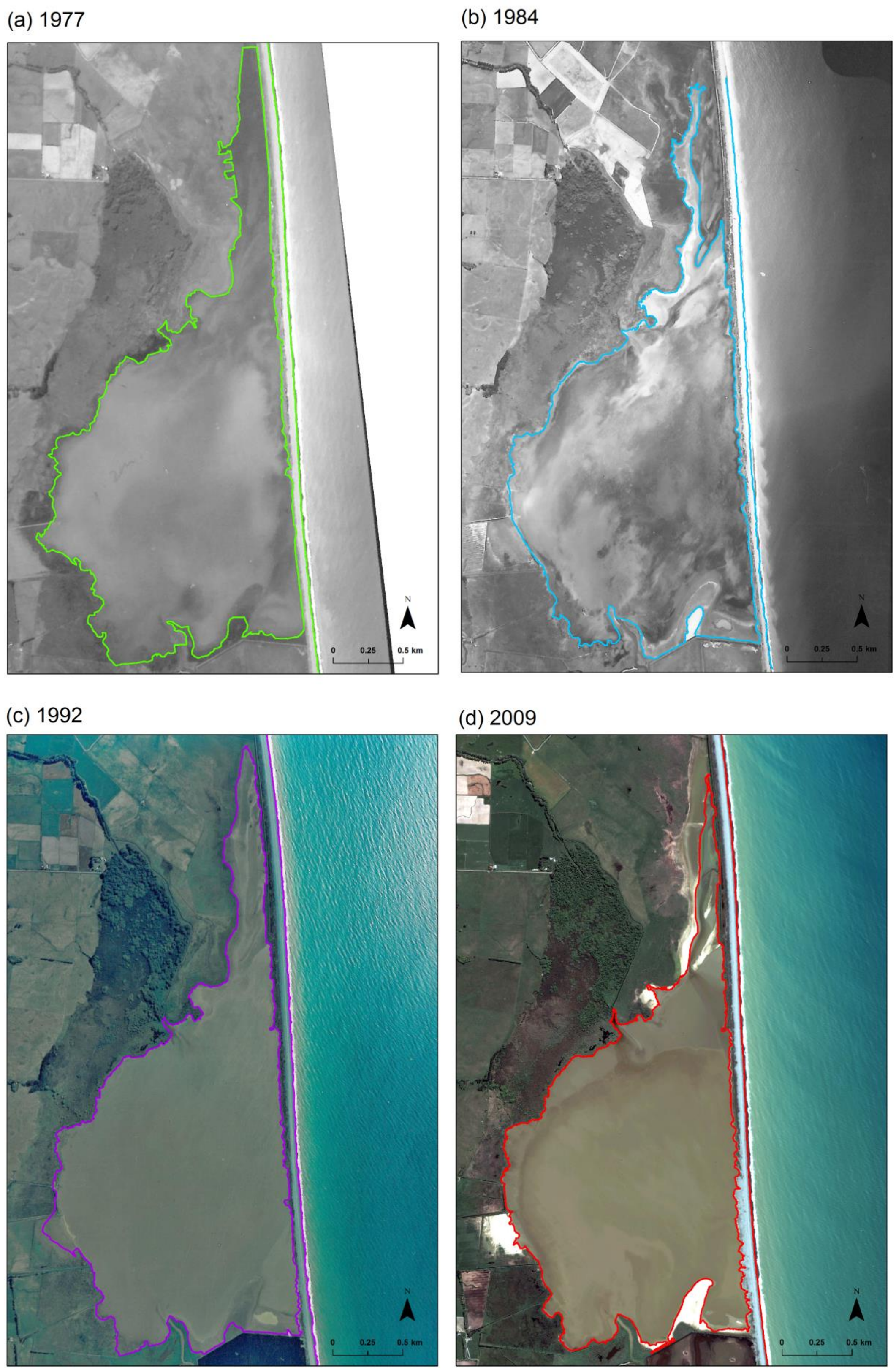


Figure 4.6. Wainono Lagoon aerial images with digitised shorelines (a) 1977, (b) 1984, (c) 1992 and (d) 2009.

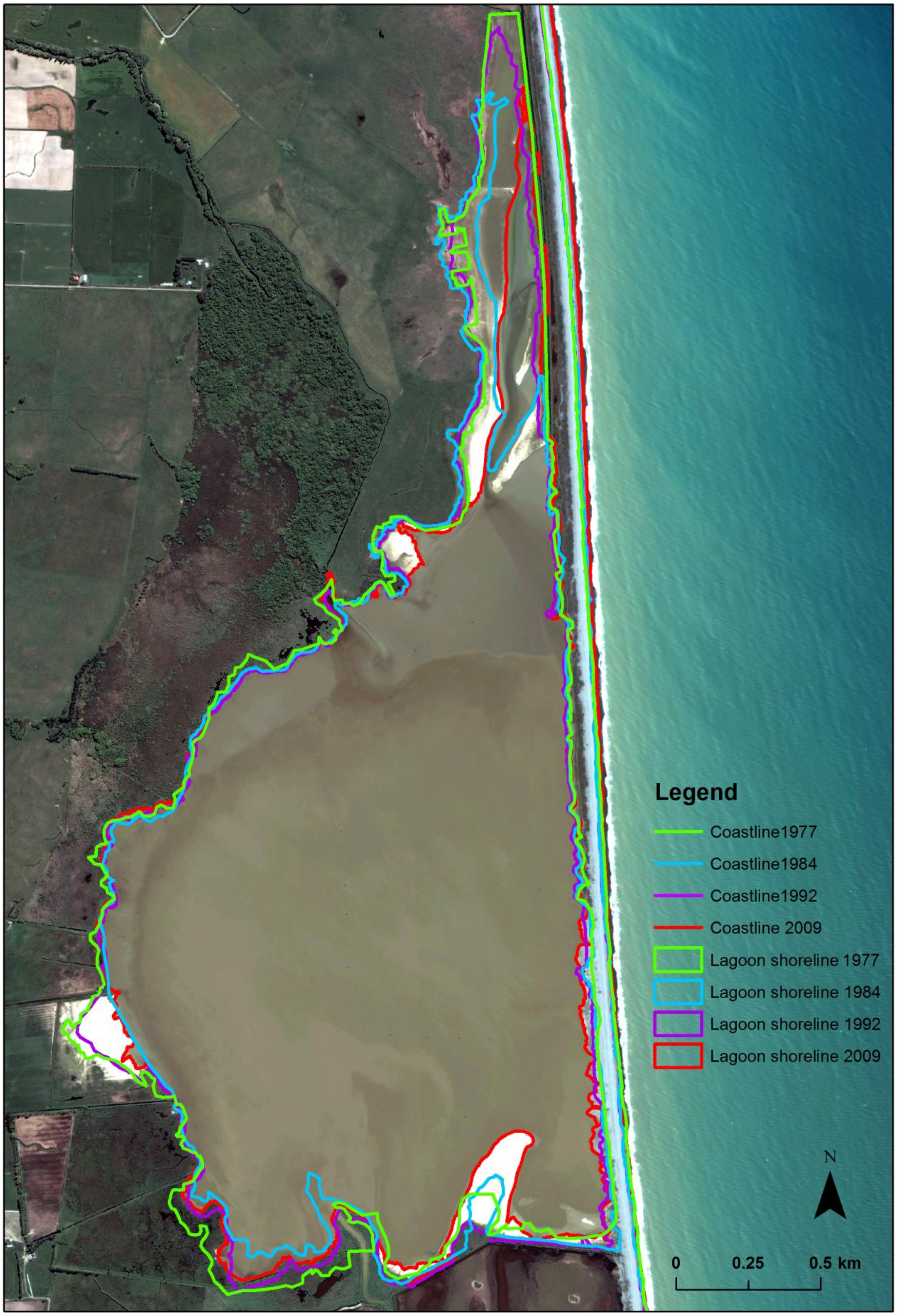


Figure 4.7. Digitized shorelines and coastlines of 1977, 1984, 1992 and 2009 overlaid on the 2009 aerial image.

Table 4.1. Changes in the surface area of Wainono Lagoon

Year	Surface area (m^2)
1977	3,857,980
1984	3,486,990
1992	3,716,080
2009	3,434,090

4.5 Summary synthesis

The results presented above in this chapter are summarised here to comprehend the recent changes in geomorphology at Wainono Lagoon. The results indicated that major morphological changes in the recent decades at Wainono Lagoon are associated with high energy events and human intervention. The beach barrier profile survey results showed significant morphological changes were caused by the artificial beach reconstruction in 1985 and the storm events in 2001 and 2002. This is highly important and relevant to the management and future scenario of Wainono Lagoon, which will be discussed in Chapter 6.

Sedimentation rates in Wainono Lagoon appear to vary spatially and temporally. The bathymetric analysis only presents a snapshot of the changes in bathymetry, however, it shows that sedimentation rates have significantly varied across at different areas in the lagoon between 2002 and 2015. The bathymetric survey results showed that the bathymetric range in the survey area has decreased between 2002 and 2015. This is congruent with the findings of Scharf et al. (2010) that the lake bed topography is smoothed out over time by preferred sediment deposition in depressions. Schallenberg and Saulnier-Talbot (2014) took a sediment core from the centre of the lagoon, to avoid the areas of episodic sediment deposition and erosion around the lagoonal margin, and calculated the accumulation rate to be 3 mm per year over the period 1912 to 2012. The accumulation rates in some parts of the survey site in the last 13 years are significantly higher than 3 mm per year. Irregular sedimentation patterns in the lagoon can result in partial infilling and shift in positions of the lagoon shoreline. Regular monitoring of the lagoon bathymetry would enable a better understanding of the sedimentation patterns and trends.

The profile survey results showed clear impacts of high energy events on the barrier morphology. The beach face morphology is susceptible to everyday wave processes as well as to periodic high energy events. Since the beach face morphology is characterised by frequent dynamics, it is important that trends are established over a long term. In contrast, the backbarrier morphology is characterised by very drastic and infrequent changes. This is because changes on the backbarrier morphology are predominantly event-driven. The beach profile excursions show that morphological changes at the backbarrier are infrequent and major changes are caused by high energy events. For this reason, the effects of sea level rise and climate change may result in drastic changes in the backbarrier morphology while effects may appear slowly over a long-term on the beach face. At Wainono Lagoon, the positions of the backbarrier shifted landward significantly after the storm events, however, translation of the entire barrier was not evident due to the insignificant long-term changes in the positions of the beach face.

The position of the backbarrier has migrated landward since 1977, but the effect of this on the lagoon size has not been conclusively established. Assessment of the digitised shoreline revealed temporal variations in the wetted perimeter as well as the consequent difficulty in assessment of lagoon shoreline change, which will be discussed further in section 6.3. The wetted perimeter is influenced by not only the morphological changes of the lagoon but also by the catchment hydrology and weather. Data for a longer timeframe are required to establish a trend in the position of the lagoon shoreline.

This chapter presented results and interpretation relating to geomorphological changes in the recent decades. The results summarised in this section will be discussed further in Chapter 6 along with the results presented in Chapter 5.

Chapter 5. Reconstruction of evolutionary and environmental history of Wainono Lagoon

5.1 Introduction

This chapter presents the results and interpretation pertaining to the reconstruction of the evolutionary and environmental history of Wainono Lagoon. Results are followed by a summary synthesis where data are analysed conjointly to infer the past environments and events, which will be discussed further in Chapter 6.

Sediment cores WLW1, WLW2, WLB1 and WLB2 retrieved from Wainono Lagoon are displayed in Figure 5.1. The visual and textural sediment characteristics were recorded and photographs were taken immediately after the cores were halved. Sediment samples were taken from these cores to analyse for grain size distribution, AMS and foraminiferal assemblage.

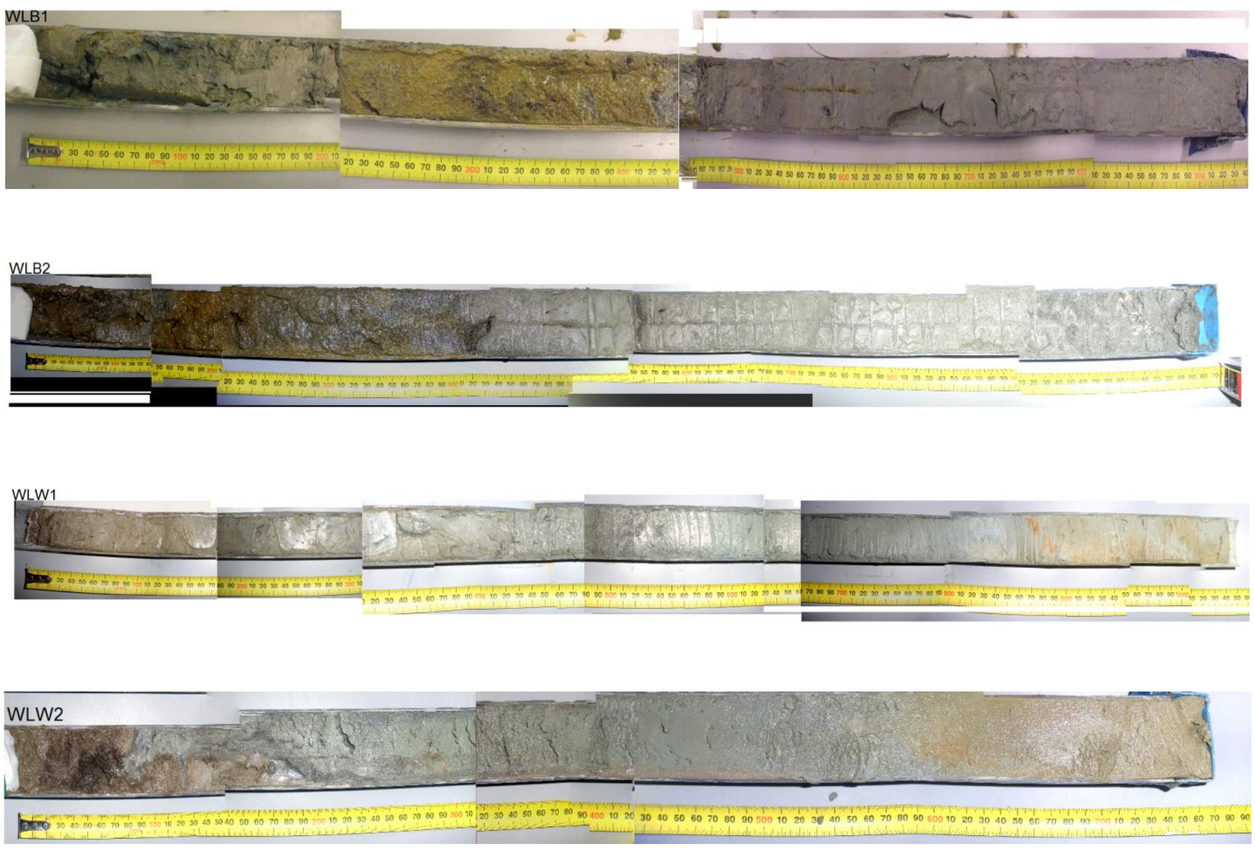


Figure 5.1. Images of sediment cores WLB1, WLB2, WLW1 and WLW2 immediately after they were halved.

5.2 Stratigraphy and sediment characteristics

Stratigraphy and sediment characteristics were examined. Visual and textual stratigraphy logs were recorded immediately after the cores were split. The logs are displayed in Figure 5.2. The colour is described according to Munsell Soil-Color Charts. The sediment texture is described according to the grain size mode (Figure 5.3) of the sample sediment.

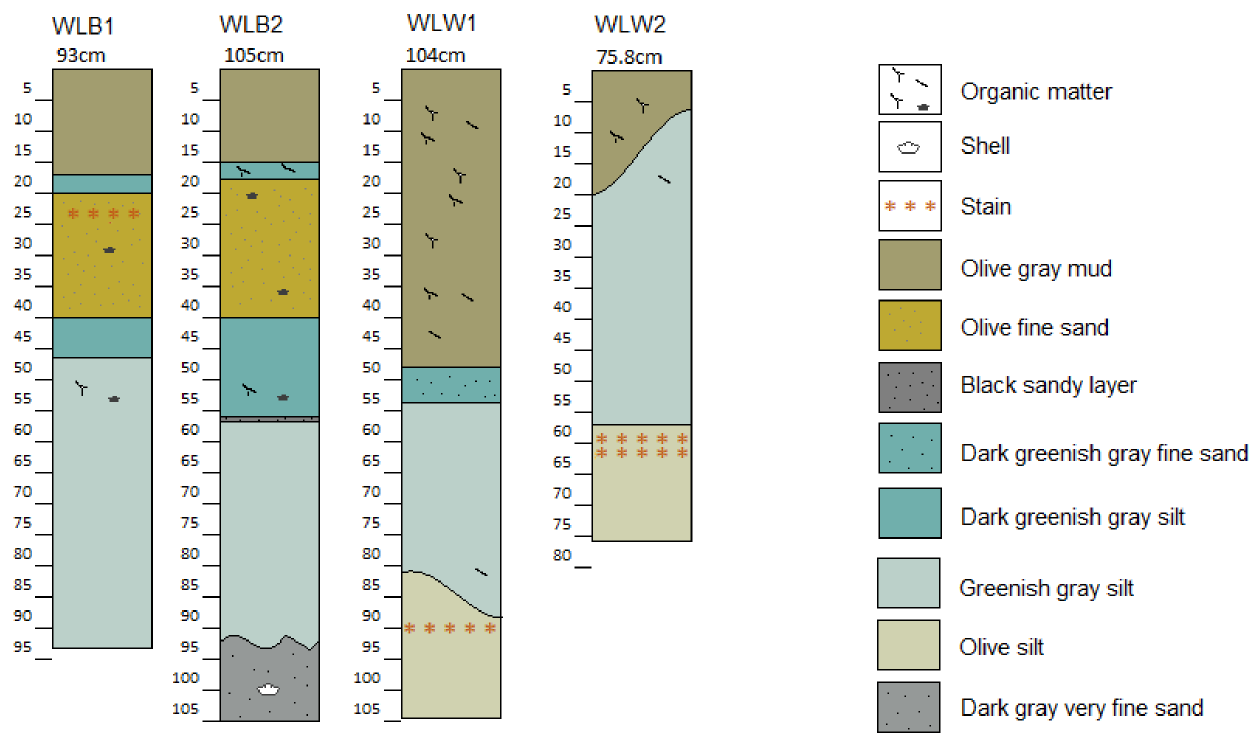


Figure 5.2. Visual and textual core stratigraphy of cores WLB1, WLB2, WLW1 and WLW2.

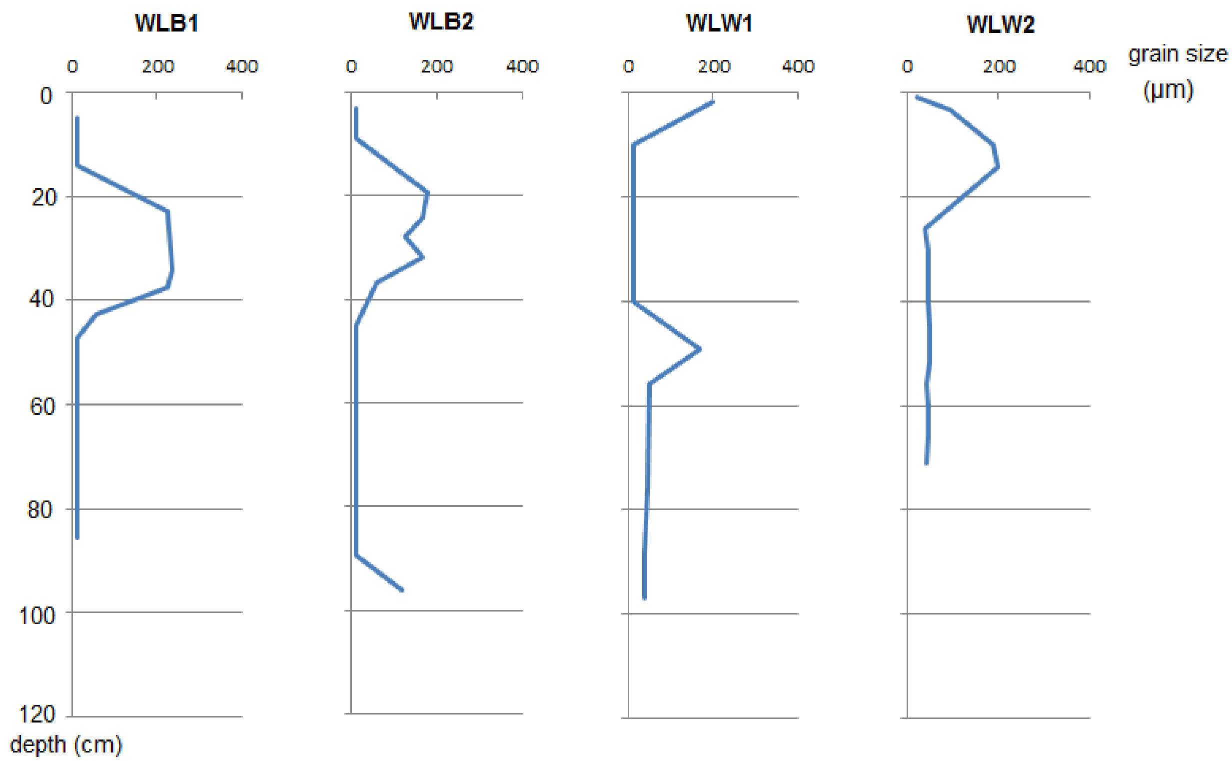


Figure 5.3. Modal grain size distribution.

Cores WLB1 and WLB2 retrieved from the barrier side displayed a similar stratigraphy. Below the recent mud deposits a dark greenish gray silt layer was present at 17.5 cm depth below surface (dbs) in WLB1 and 15 cm dbs in WLB2. The silt layer in WLB1 and WLB2 was interrupted by 20 cm and 22.5 cm thick distinctive sand layers respectively. The olive coloured sand was very saturated and fragments of charcoal were observed within the sand section. A 2 mm thin black layer with sandy texture was present in WLB2 at 56 cm, but this was not found in WLB1. The dark greenish gray silt layer gradually became lighter in colour to greenish gray. At 92 cm dbs in WLB2 a dark gray very fine sand layer was present. The surface of this layer was rippled and broken up shell pieces were present in the layer.

Cores WLW1 and WLW2, from the western edge of lagoon, displayed a similar stratigraphy. A sandy layer found in WLW1 was not mirrored in WLW2. The olive coloured silt section in WLW1 and WLW2 is likely the greenish gray silt having been weathered by subaerial processes due to a lowered water level. The stained silt at 87 – 91.5 cm dbs in WLW1 matched 58 – 62 cm dbs of WLW2. The disconformities at 81.5 – 87 cm dbs in WLW1 and 7.5 - 20 cm dbs in WLW2 are likely the result of erosion caused by a channel or fluctuations in water level.

The modal grain size distribution in the surface mud, in WLW1 and WLW2, displays inconsistency as shown in Figure 5.3. The modal grain size of samples from the section 0 – 47.5 cm dbs in WLW1 and 0 – 20 cm dbs in WLW2 ranges from 11.5 to 199.6 μm and from 20.0 to 199.6 μm respectively. This irregularity in grain size mode is explained by the high organic content.

The greenish gray silts appear to be the predominant type of sediment below the surface mud deposition in all cores. The grain size in this section is generally coarser in WLW1 and WLW2 compared to the barrier side equivalent in WLB1 and WLB2. The modal grain size of this section in WLB1 and WLB2 is typically 10.6 μm whereas the modal grain size in WLW1 and WLW2 varies between 39.8 and 50.1 μm. This indicates that WLW1 and WLW2 are closer to the sediment source. This is discussed further in section 5.5.

5.3 Anisotropy of Magnetic Susceptibility and grain size

The AMS technique was used to infer the hydrodynamic conditions including flow directions and energy levels that existed during the settling phase of the sediments. AMS was measured for samples taken from cores WLW2, WLB1 and WLB2. The results are analysed in conjunction with the grain size data to maximise the information regarding the hydrodynamic conditions at the time of the settling phase of the sediments. Figure 5.4 displays a synthetic diagram of equal areas, lower hemisphere projections of the principal AMS axes for samples from cores WLB1, WLB2 and WLW2. The AMS results with grain size data are summarised in Table 5.1.

Sand deposits in cores WLB1 and WLB2 displayed anomalies in flow direction. While the majority of K1 plots in core WLB1 displayed a westerly flow, samples from a sandy layer displayed flows from the south (WLB1.4) and from the north (WLB1.5 and WLB1.6). The modal grain size distribution in samples WLB1.4, WLB1.5 and WLB1.6 was anomalously large (> 220 µm) compared to other sections as shown in Table 5.1. Samples from core WLB2 displayed a dominant flow from the east with exceptions of sand deposits. Samples with modal grain size distribution of > 59 µm, which include sand and coarse silts, displayed flows from the south (WLB2.3) and north (WLB2.4, WLB2.5, WLB2.6 and WLB2.16).

Samples from core WLW2 displayed flows from the north, except WLW2.6 and WLW2.14 displayed flows from the south. A clear relationship between the flow direction and grain size distribution was not established for core WLW2.

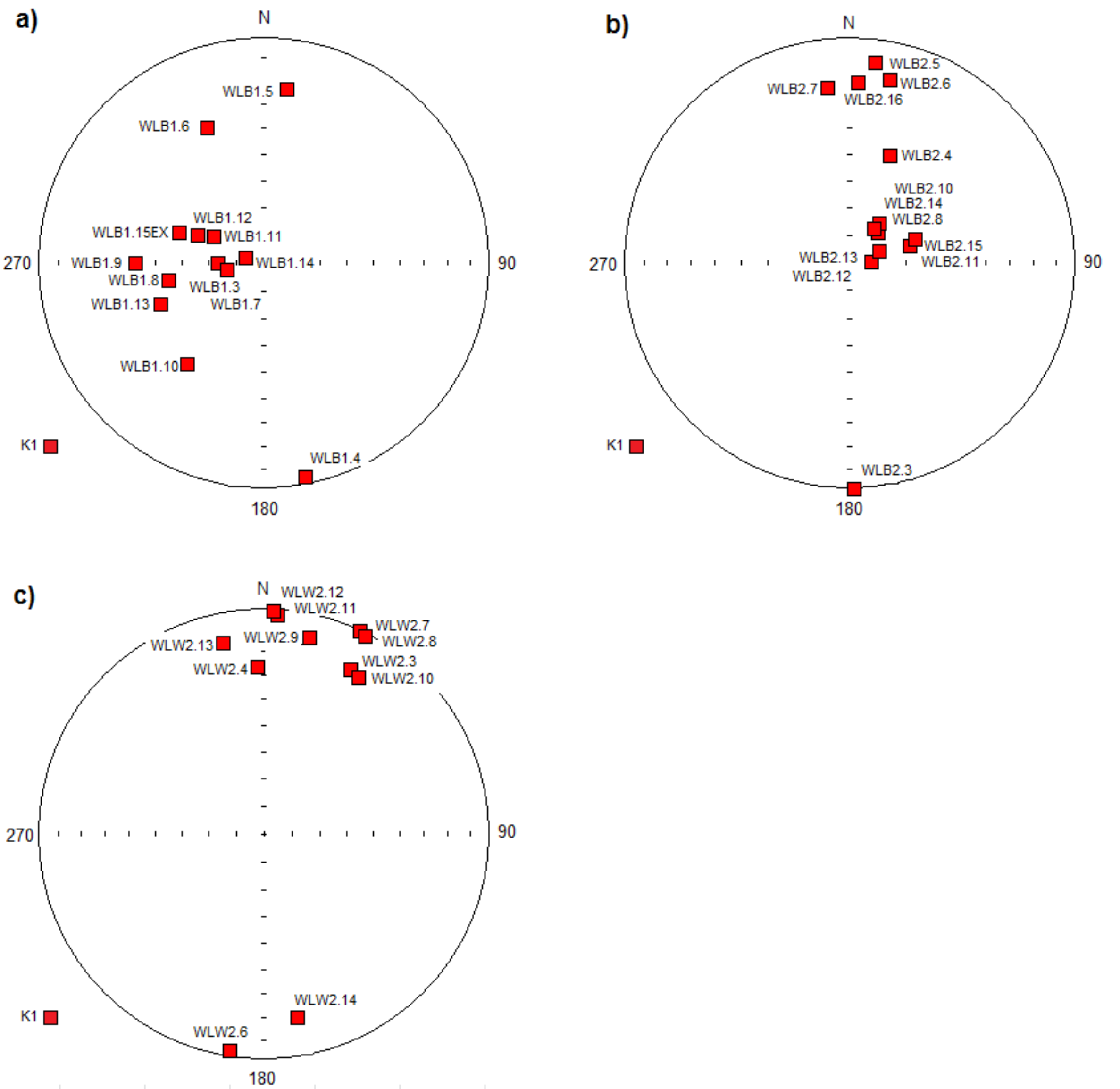


Figure 5.4. Equal areas for a) core WLB1, b) core WLB2 and c) core WLW2. K1 plots represent the flow direction and inclination during the sediment deposition.

Table 5.1. AMS results with grain size. K mean: bulk magnetic susceptibility, D°: declination, I°: inclination, L: magnetic lineation, F: magnetic foliation, Pj: corrected anisotropy degree, T: shape parameter.

			Max Axis (K1)		Int Axis (K2)		Min Axis (K3)						Grain size (µm)		
Sample	Depth (cm)	K mean	D°	I°	D°	I°	D°	I°	L	F	Pj	T	Mean	Median	Mode
WLB1.3	14	-2.49E-07	270.7	73.1	126.5	13.9	34.1	9.5	-3.750	0.071	0.000	0.000	21.558	17.345	10.594
WLB1.4	23	-2.22E-06	169.2	4.2	267.3	62.2	77.0	27.4	1.565	2.156	3.423	0.263	109.288	99.454	223.903
WLB1.5	34	3.51E-04	7.6	23.5	123.4	45.1	259.5	35.6	1.015	1.002	1.019	-0.736	135.302	140.592	237.170
WLB1.6	37.6	4.01E-04	337.4	35.1	125.2	50.3	235.6	16.2	1.009	1.009	1.018	0.033	118.687	120.864	223.903
WLB1.7	42.5	3.67E-04	260.1	76.2	64.0	13.3	154.9	3.7	1.002	1.026	1.031	0.850	46.072	32.272	56.242
WLB1.8	47.3	2.38E-04	259.6	54.4	102.7	33.3	5.4	11.0	1.003	1.024	1.030	0.747	22.784	12.798	11.222
WLB1.15 EXTRA	54.3	4.44E-04	289.8	56.9	71.3	27.0	170.6	17.6	1.015	1.017	1.033	0.046	13.928	8.709	10.908
WLB1.9	62	1.61E-04	270.2	42.4	142.3	33.9	30.5	28.9	1.009	1.009	1.018	0.029	11.519	7.945	10.594
WLB1.10	68	1.78E-04	217.6	43.3	321.2	14.0	64.8	43.3	1.014	1.006	1.021	-0.359	11.891	7.819	10.594
WLB1.11	74	1.72E-04	298.1	69.3	67.1	13.4	160.8	15.5	1.013	1.005	1.019	-0.491	10.312	6.495	10.594
WLB1.12	77.5	1.33E-04	292.5	63.9	83.6	23.2	178.5	11.3	1.023	1.001	1.028	-0.997	10.227	6.148	10.594
WLB1.13	81.2	1.84E-04	248.3	48.9	16.5	28.4	122.5	27.1	1.007	1.007	1.014	0.041	9.253	5.824	10.594
WLB1.14	85.4	1.26E-04	285.0	83.0	56.1	4.6	146.5	5.3	1.014	1.014	1.031	-0.085	12.457	6.887	10.594
WLB2.3	19.2	3.79E-04	178.9	0.0	88.7	80.8	268.9	9.2	1.005	1.005	1.017	-0.424	97.535	91.480	177.852
WLB2.4	24.3	3.08E-04	20.0	47.8	112.6	2.4	204.8	42.1	1.003	1.003	1.017	-0.634	94.651	89.175	167.903
WLB2.5	28	3.86E-04	7.3	11.7	97.5	0.9	192.1	78.3	1.021	1.002	1.026	-0.804	92.216	92.775	125.910
WLB2.6	31.7	5.42E-04	12.2	17.9	181.1	71.7	281.1	3.3	1.009	1.013	1.022	0.205	124.108	120.812	167.903
WLB2.7	36.7	5.55E-04	352.7	22.8	94.6	26.1	227.2	54.1	1.010	1.007	1.017	-0.165	49.835	37.617	59.574
WLB2.8	45	1.52E-04	42.0	75.0	156.1	6.2	247.6	13.6	1.015	1.006	1.022	-0.404	23.712	13.287	11.222
WLB2.10	61.7	1.30E-04	36.4	72.4	284.1	6.9	192.1	16.2	1.021	1.006	1.028	-0.545	12.669	8.046	10.594
WLB2.11	67	1.50E-04	73.6	67.5	281.4	20.2	187.8	9.7	1.014	1.012	1.026	-0.065	11.115	7.194	10.594
WLB2.12	74.4	1.39E-04	87.5	82.5	226.6	5.7	317.1	4.9	1.029	1.005	1.037	-0.711	9.261	5.986	10.594
WLB2.13	79.5	1.14E-04	66.5	78.8	197.7	7.5	288.8	8.4	1.011	1.001	1.014	-0.807	8.969	5.681	10.594
WLB2.14	84.5	1.11E-04	35.3	74.7	129.7	1.2	220.1	15.2	1.015	1.015	1.030	0.009	9.187	5.704	10.594
WLB2.15	89.2	1.42E-04	70.0	64.9	268.7	23.9	175.5	7.1	1.016	1.016	1.032	0.011	24.925	8.336	10.594
WLB2.16	96	2.02E-04	2.5	21.1	247.7	47.5	108.1	34.9	1.023	1.014	1.038	-0.230	68.159	60.507	118.866
WLW2.3	10	7.03E-05	27.8	18.8	182.9	69.4	295.1	8.1	1.010	1.009	1.019	-0.068	78.931	49.904	188.391
WLW2.4	14.2	8.61E-05	357.7	26.5	97.6	19.0	218.9	56.5	1.017	1.005	1.023	-0.579	71.725	44.844	199.554
WLW2.6	26	1.05E-04	189.1	3.4	279.6	8.4	77.3	81.0	1.008	1.005	1.013	-0.207	36.215	25.719	39.816
WLW2.7	30.5	1.15E-04	25.3	0.2	294.9	60.8	115.4	29.2	1.005	1.009	1.014	0.268	35.32	27.074	44.674
WLW2.8	40.5	1.11E-04	27.1	2.1	117.5	10.4	285.7	79.4	1.012	1.003	1.016	-0.626	39.132	30.662	44.674
WLW2.9	45	1.10E-04	12.8	11.5	281.3	7.7	158.1	76.1	1.009	1.007	1.016	-0.156	40.218	32.101	50.126
WLW2.10	51.5	1.36E-04	31.3	20.2	138.7	39.1	280.4	44.0	1.005	1.009	1.014	0.264	42.835	32.774	50.126
WLW2.11	56	1.59E-04	3.3	3.2	268.0	59.2	95.2	30.6	1.014	1.008	1.023	-0.253	36.476	26.586	42.175
WLW2.12	60	1.80E-04	2.3	1.1	271.8	23.0	94.9	67.0	1.015	1.002	1.019	-0.717	44.522	32.773	47.322
WLW2.13	66	1.82E-04	347.8	14.3	223.3	65.8	82.9	19.1	1.013	1.008	1.022	-0.261	43.884	32.759	44.674
WLW2.14	71	1.91E-04	169.9	18.6	13.5	69.8	262.4	7.5	1.045	1.019	1.067	-0.405	43.885	31.280	42.175

5.4 CM diagram

The sand deposits (samples WLB1.4, WLB1.5, WLB1.6, WLB2.3, WLB2.4, WLB2.5, WLB2.6 and WLB2.16) have been displayed in a CM diagram (Figure 5.5) to examine the transport mechanism at the time of deposition. The results from this study in terms of the CM diagram are discussed in the following paragraph.

Figure 5.5 and Table 5.2 shows the emplacement mechanism was gradual suspension for the olive coloured sand section (20 – 40 cm dbs in WLB1 and 17.5 – 40 cm dbs in WLB2) and uniform suspension for sample WLB2.16. This is a significant contrast to sediments in the greenish gray silt layer below 40 cm dbs in WLB1 and WLB2 which represents very low energy conditions represented by C95 value of 55.3 µm median values of 16 µm on average.

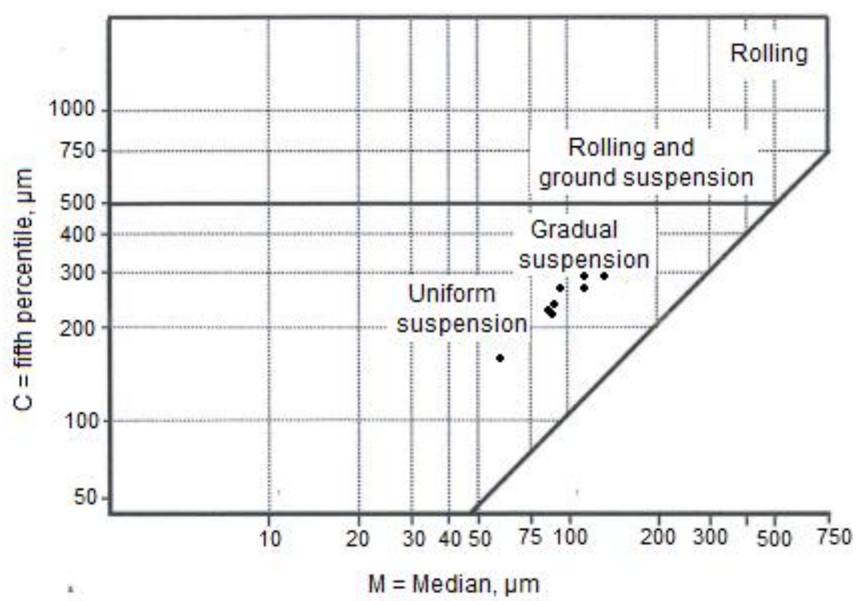


Figure 5.5. CM diagram: the sand deposits in WLB1 and WLB2. Sample WLB2.16 suggests an emplacement mechanism of uniform suspension and samples WLB1.4, WLB1.5, WLB1.6, WLB2.3, WLB2.4, WLB2.5 and WLB2.6 suggest an emplacement mechanism of gradual suspension.

Table 5.2.C95 values and inferred emplacement mechanisms for sand deposits.

Sample	C95	Emplacement mechanism
WLB1.4	271.4	Gradual suspension
WLB1.5	289.4	
WLB1.6	271.5	
WLB2.3	237.8	
WLB2.4	236.0	
WLB2.5	217.6	
WLB2.6	288.6	
WLB2.16	175.5	Uniform suspension

5.5 Foraminiferal analysis

Foraminiferal assemblages in cores WLW1, WLW2, WLB1 and WLB2 were analysed to infer the salinity range of the past environments. The results are displayed in Figure 5.6. No foraminifera were found in any of the samples from WLW1 and WLW2.

Sections 5 - 10 cm dbs in WLB1 and 4.5 - 7.5 cm dbs in WLB2 contained a large number of *Miliammina fusca* and small numbers of *Trochamminita salsa.* Presence of these species indicates intertidal environments with very low salinity around or below Mean High Water (MHW) (Hayward et al., 1999).

In the section 100 - 108 cm dbs of WLB2, the assemblage was dominated by *Ammonia parkinsoniana*, with small numbers of *Elphidium advenum*. These species are generally common in a brackish to slightly brackish environments below MHW, rather than fully marine (Hayward et al., 1999). According to Jorissen (1988) *Ammonia parkinsoniana* can also survive in stressful environments, such as river mouths that experience occasional flooding, although the fact this specie was not present in any other sections indicates that this particular section of 100 - 108 cm dbs was most likely constantly exposed to a mixing of fresh and sea waters. Presence of *Elphidium advenum* indicates salinity of about >22 ppt. It is reasonable to interpret that there was a tidal inlet along the Wainono barrier and constant mixing of freshwater and marine water occurred over a prolonged period when these sediments were deposited.

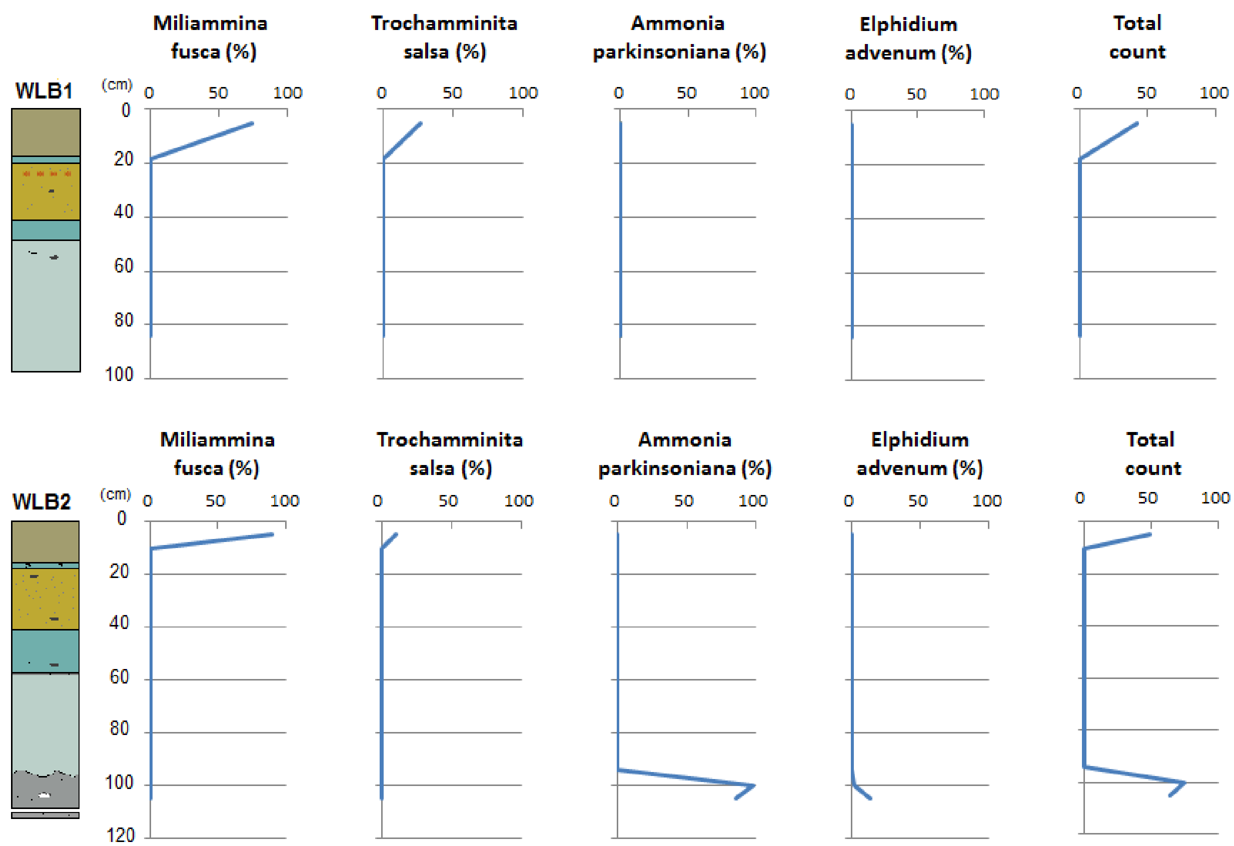
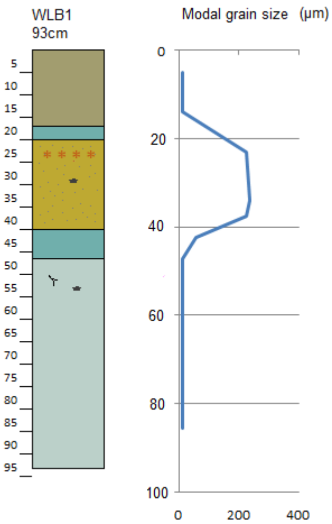


Figure 5.6. Results of the foraminiferal analysis. The percentile and total count data in WLB1 and WLB2.

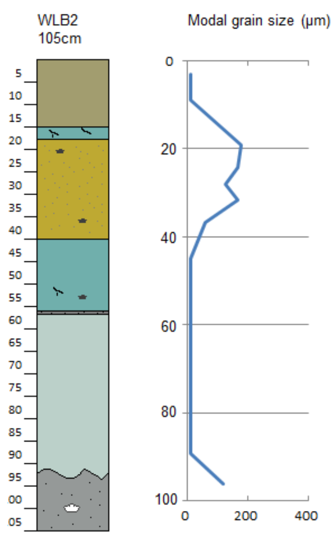
5.6 Summary synthesis

The results presented in this chapter allow inference of hydrodynamics and environment at the time of sediment deposition. In this section, an evolutionary and environmental history of Wainono Lagoon inferred by the combination of AMS, grain size and foraminiferal analyses (Figure 5.7) is presented.

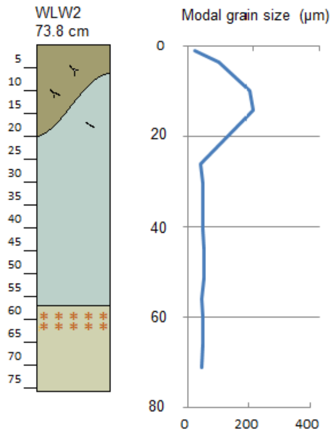
The dates of events are unknown since radio carbon dating or Pb210 dating was not conducted. Nevertheless, it is estimated that core WLB would cover approximately 300 years. This is based on the averaged sedimentation rate of 3 mm per year established by Schallenberg and Saulnier-Talbot (2014). Based on their rate of sedimentation, core WLB2 would cover approximately 350



Sample	depth (cm)	GS range (µm)	K1 D°	K1 I°	K2 D°	K2 I°	Interpretation
WLB1.3	14	0.61 - 193.87	270.7	73.1	126.5	13.9	Flow from West
WLB1.4	23	0.58 - 307.26	169.2	4.2	267.3	62.2	Flow from South
WLB1.5	34	0.55 - 325.46	7.6	23.5	123.4	45.1	Flow from North
WLB1.6	37.6	0.52 - 307.26	337.4	35.1	125.2	50.3	Flow from North-West
WLB1.7	42.5	0.73 - 230.41	260.1	76.2	64.0	13.3	Flow from West
WLB1.8	47.3	0.65 - 172.78	259.6	54.4	102.7	33.3	Flow from West
WLB1.15extra	54.3	0.58 - 86.60	289.8	56.9	71.3	27.0	Flow from West
WLB1.9	62	0.58 - 54.64	270.2	42.4	142.3	33.9	Flow from West
WLB1.10	68	0.58 - 61.31	217.6	43.3	321.2	14.0	Flow from South-West
WLB1.11	74	0.55 - 54.64	298.1	69.3	67.1	13.4	Flow from West
WLB1.12	77.5	0.55 - 54.64	292.5	63.9	83.6	23.2	Flow from West
WLB1.13	81.2	0.55 - 48.70	248.3	48.9	16.5	28.4	Flow from South-West
WLB1.14	85.4	0.55 - 86.60	285.0	83.0	56.1	4.6	Flow from West



Sample	depth (cm)	GS range (µm)	K1 D°	K1 I°	K2 D°	K2 I°	Interpretation
WLB2.3	19.2	0.55 - 307.26	178.9	0.0	88.7	80.8	Flow from South
WLB2.4	24.3	0.69 - 307.26	20.0	47.8	112.6	2.4	Flow from North
WLB2.5	28	0.65 - 290.07	7.3	11.7	97.5	0.9	Flow from North
WLB2.6	31.7	0.65 - 365.17	12.2	17.9	181.1	71.7	Flow from North
WLB2.7	36.7	0.73 - 230.41	352.7	22.8	94.6	26.1	Flow from North
WLB2.8	45	0.69 - 217.52	42.0	75.0	156.1	6.2	Flow from North-East
WLB2.10	61.7	0.58 - 64.94	36.4	72.4	284.1	6.9	Flow from North-East
WLB2.11	67	0.58 -54.64	73.6	67.5	281.4	20.2	Flow from North-East
WLB2.12	74.4	0.55 - 45.97	87.5	82.5	226.6	5.7	Flow from East
WLB2.13	79.5	0.55 - 45.97	66.5	78.8	197.7	7.5	Flow from East
WLB2.14	84.5	0.55 - 48.70	35.3	74.7	129.7	1.2	Flow from South-West
WLB2.15	89.2	0.55 - 163.12	70.0	64.9	268.7	23.9	Flow from East
WLB2.16	96	0.65 - 230.41	2.5	21.1	247.7	47.5	Flow from North



Sample	depth (cm)	GS range (µm)	K1 D°	K1 I°	K2 D°	K2 I°	Interpretation
WLW2.3	10	0.65 - 273.84	27.8	18.8	182.9	69.4	Flow from North-East
WLW2.4	14.2	0.65 - 273.84	357.7	26.5	97.6	19.0	Flow from North
WLW2.6	26	0.58 - 183.02	189.1	3.4	279.6	8.4	Flow from South
WLW2.7	30.5	0.61 - 153.99	25.3	0.2	294.9	60.8	Flow from North-East
WLW2.8	40.5	0.61 - 172.78	27.1	2.1	117.5	10.4	Flow from North-East
WLW2.9	45	0.61 - 172.78	12.8	11.5	281.3	7.7	Flow from North
WLW2.10	51.5	0.61 - 193.87	31.3	20.2	138.7	39.1	Flow from North-East
WLW2.11	56	0.58 - 172.78	3.3	3.2	268.0	59.2	Flow from North
WLW2.12	60	0.58 - 217.52	2.3	1.1	271.8	23.0	Flow from North
WLW2.13	66	0.58 - 193.87	347.8	14.3	223.3	65.8	Flow from North
WLW2.14	71	0.58 - 217.52	169.9	18.6	13.5	69.8	Flow from South

Figure 5.7. Synthesis of data used for the reconstruction of historical events and environments. Stratigraphy, modal grain size distribution, gran size range are presented. Flow directions were interpreted from orientation and inclination of the maximum axis and inclination of the intermediate axis.

years, or approximately 280 years if the 20 cm sand layer was deposited by one event. Although sedimentation rates in pre-European times can be considerably lower (Schallenberg et al., 2012), a generous assumption is made here that core WLB2 (105 cm dbs + nosepiece) covers approximately 300 years. The bathymetric analysis showed that sedimentation in the lagoonal margin was very dynamic and characterised by spatial and temporal irregularity. It is stressed that the time suggested in this study is only an estimation ignoring the spatial and temporal variation in sedimentation over a centurial scale.

The section below 95 cm dbs in WLB2 suggests that Wainono Lagoon was in an estuarine phase. There was at least one inlet along the barrier, north of the coring site, and the lagoon was exposed to tides. The estuarine phase has been inferred due to the evidence of the coarse sediments, the flow from the north as well as the foraminiferal assemblage indicating tidal conditions and a brackish environment with mixing of fresh and marine water within the lagoon. It is unknown when and why the lagoon switched to an estuarine phase, however, the estuarine period lasted at least decades and possibly longer, using the Schallenberg et al. accumulation rate assumption.

It is likely the water level was lowered when the barrier was open during the estuarine phase. The stains in the olive coloured silt at 87 cm dbs in WLW1 and 57 cm dbs in WLW2 are likely to be a result of oxidation during exposure to air under conditions with a lowered water level. The stains correspond with the tidal phase indicated by the sandy section of WLB2 (below 105 cm dbs). Alternatively the olive coloured (yellow-brown) silt (Young, 1967) was deposited by aeolian transport.

After Wainono Lagoon was in an estuarine phase for a prolonged period of time, the core evidence suggests the barrier became fully established and closed the lagoon off from the sea. This closure was likely produced by processes similar to those operating along this coast today - namely by wave actions and longshore currents transporting sediment along the barrier's seaward shore. Wainono Lagoon became an enclosed lagoon-wetland complex. This period is connoted by the greenish gray silt present in all cores. Evidence of marine influences was not found in this layer, although it is anticipated that the barrier was breached occasionally during high energy events. The lagoon was fresh-water-dominated and the lagoonal sediment source was predominantly fluvial. The eastern side sediments (WLB1 and WLB2) presented smaller grain sizes (both mode and median) compared to those on the western side (WLW1 and WLW2). This is consistent with theory which indicates that in a fluvial-dominated delta or lagoon, coarse sediments accumulate around the river mouth and finer sediments are deposited further away (Bird, 1994; Boggs, 2012; G. Nichols, 2009). This explains the finer grain size distribution at the barrier side in the lagoon.

Sediment grain size shows a slight increase at 46 cm dbs in WLB1, 56 cm dbs in WLB2, 87 cm dbs in WLW1 and 57 cm dbs in WLW2. This most likely corresponds to the arrival of the Europeans and changes in land-cover and land-use around 100 – 150 years B.P. During this period, farm drains and the Waihao Box were constructed. A large part of the wetland was drained and the lagoon level was significantly lowered (Schallenberg & Saulnier-Talbot, 2015).

Sediment core analyses found that a large amount of sediment was deposited on the bed of Wainono Lagoon by an extreme event. This event was evident in the core layer from 20 - 40 cm dbs in WLB1 and 17.5 - 40 cm dbs in WLB2. The barrier was breached north of the WLB coring sites and coarse sediments were deposited by a series of southward moving flows (starting N337.4° – N352.7° range followed by N73° - N20.0° range) with a gradual decrease in energy followed by a strong flow from the south (N169.2° - N178.9°). This flow pattern can be interpreted as a tsunami run-up and backwash and suggests that the event was caused by a tsunami wave or fluctuation in water level associated with a tsunami. This will be discussed further in detail in Chapter 6.

The mud layer above 17 cm dbs in WLB1, 15 cm dbs in WLB2, 48.5 cm dbs in WLW1 and 20 cm dbs in WLW2 is characterised by a brackish low-energy environment. The foraminiferal assemblage, dominated by *Miliammina fusca* with the presence of *Trochamminita salsa*, suggests very low salinity. While the lagoon has had a connection to the sea at times, it is usually enclosed with a fully established barrier.

A core from the western edge of the lagoon, WLW2, evidenced a relatively stable energy environment throughout its length. This site is by the drain outlet located on the edge of the wetland. Apart from the recent muddy section, which had high organic matter content, there were no significant changes in the grain size distribution. The sediment core below the muddy section comprised silt derived from fluvial sources. The absence of foraminifera in WLW1 and WLW2 was likely because this site has been a freshwater dominated environment. The stained silt also indicates that the sediment was exposed to air sometime after deposition. The ground was exposed when the water level was low. This condition could have been associated with a drought, an estuarine phase when the lagoon had a relatively large opening, or possibly with a sea level drop.

This chapter presented the results and interpretation pertaining to the reconstruction of the evolutionary and environmental history of Wainono Lagoon. The summary synthesis presented in this section will be discussed further in Chapter 6.

Chapter 6. Discussion

6.1 Introduction

The results and interpretation were presented in Chapter 4 and 5. This chapter provides a more detailed discussion of the inferred history of Wainono Lagoon and a conceptual context. Data from this research and previous studies have been compiled to present a comprehensive history of Wainono Lagoon as well as the recent trends. The knowledge of the past behaviour of the lagoon, recent trends in morphology, anthropogenic influences, historical/cultural values and potential hazards is crucial information for sustainable lagoon management. Upon comprehension of the Wainono Lagoon system and its long term stability, the management strategies for Wainono Lagoon are reviewed in this chapter. The findings are linked and discussed in relation to existing literature and theories. Finally, the summary section outlines how the thesis has addressed the research objectives and the research questions are answered.

6.2 The evolution and environmental history of Wainono Lagoon

Data from this research and previous studies have been collated to reconstruct an evolutionary and environmental history of Wainono Lagoon. The evolutionary typology suggested by Forbes et al. (1995), which was introduced in Chapter 1 Figure 1.2, is broadly applicable to the evolutionary history of the Wainono barrier. The stages of self-organisation model have been incorporated into a bespoke schematic evolutionary history of Wainono Lagoon as shown in Figure 6.1

The 'initiation stage' of the Wainono barrier (Figure 6.1a) is estimated to have begun around 6,000 years B.P. when the sea level (Gibb, 1986) became stable. The rates of early Holocene sea level rise were much higher than those of the present day. Rates exceeding 10 mm / year were commonly recorded for the early Holocene in contrast to the global rate of 3 mm / year today (Cronin, 2012). Barriers are generally vulnerable to destruction during remobilisation of barrier sediments

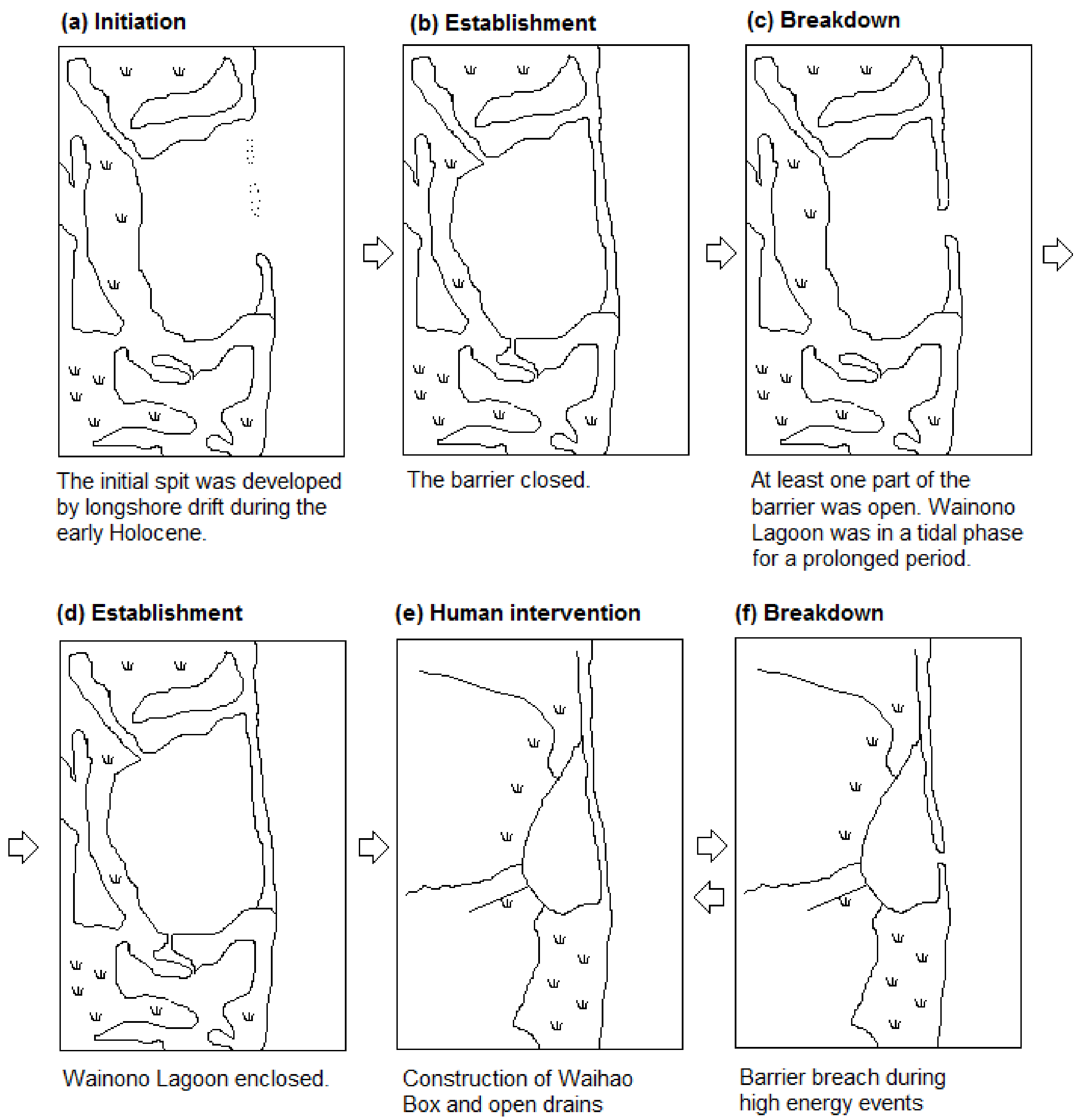


Figure 6.1. Schematic evolutionary history of Wainono Lagoon developed by compilation of data from this research and previous studies. (a) Approximately 6,000 years B.P. a spit began to develop. (b) It is assumed that the barrier was eventually fully established. The time is unknown. (c) An inlet(s) was present and the lagoon was in a tidal phase for a prolonged period of time. The time is unknown. (d) The barrier enclosed the lagoon. (e) Since the 1890s the water level has been lowered by human intervention and the lagoon surface area has been reduced accordingly. A large part of the wetland was drained and the Waihao Box was constructed. (f) The barrier breaches during high energy events. The breach is temporary and followed by re-establishment of the barrier.

(R. W. G. Carter et al., 1989). If a barrier was already developed at Wainono, it would likely have fragmented during the process of translation associated with the rapid sea level rise. Therefore this study adopts the view that the Wainono barrier was not completely formed around 6,000 years B.P. and the spit was developed by the strong northerly movement of sediments along the coast. The elevated lobe at the south-eastern corner of the lagoon may be an original spit development at the time of sea level high-stand. The timeframe of development remains unknown and therefore the time of the 'establishment stage' (Figure 6.1b) is unclear. It is assumed that the first establishment of the barrier occurred before the estuarine phase.

The 'breakdown stage' (Figure 6.1c) was evident in the sediment core. A long-term opening of the barrier was evident below 92 cm dbs in WLB2. The lagoon was characterised by a tidal phase which lasted at least for decades or longer. This 'breakdown stage' was followed by an 'initiation stage' (Figure 6.1d) again to redevelop the barrier. Wainono Lagoon was then characterised by an extensive freshwater-dominated lagoon-wetland complex until the arrival of the Europeans.

Since the 1890s onwards, the hydrology of Wainono Lagoon was altered significantly by human interventions (Figure 6.1e). The drainage of wetland and construction of the Waihao Box reduced the lagoon size significantly. The lagoon became a brackish to slightly brackish environment due to the artificial outlet to the sea which intermittently formed connection to the sea. Although evidence was not detected in sediments, short-term barrier breaches are expected to have occurred during significant storms. The 2 mm black sandy section at 56 cm dbs in WLB2 is likely a marine deposit during a high energy event, possibly a deposition from the 1868 tsunami which was the largest reported tsunami in South Canterbury. In the mid-20th century, an extreme event breached the Wainono barrier and deposited a large amount of marine sediment on the barrier side of the lagoon. This barrier breach is one established evidence of the recent "breakdown stage" of the Wainono barrier (Figure 6.1f).

The Wainono barrier has repeated the processes of 'breakdown' and 'establishment'. The evolutionary model of coarse-clastic barriers on a transgressive coast established by Forbes et al. (1995) is applicable to the Wainono barrier which is a mixed sand and gravel barrier on a transgressive coast. In general, the key drivers of the breakdown process are high energy events and sediment starvation (Forbes et al., 1995). Important components involved in the re-establishment process are the sea level, geometry, wave action and sediment availability. These factors govern the ability to redevelop the barrier.

The finding of the estuarine phase is congruent with the situation at Te Waihora/Lake Ellesmere which was also found to have been in an estuarine phase at least twice since the initial establishment of the barrier (Hemmingsen, 1997; Soons et al., 1997). At Te Waihora/Lake Ellesmere, the openings of the barrier were caused by the avulsion of the Waimakariri and/or Rakaia Rivers and associated high flows in the late Holocene. The cause of the estuarine phase at Wainono Lagoon is unknown but could have been initiated by a high energy event such as a major storm or tsunami.

It is established here that the repeated process of barrier breakdown and establishment is one of the past characteristics of a waituna-type lagoon. This differs from the present day characteristics of the waituna-type lagoons that "openings to the sea are rare and short-lived unless created by human action" stated by (Kirk & Lauder, 2000, p. 16). This also differs from the description of the 'type A' estuary (coastal lakes) classified by Hume et al. (2007) which is described as an enclosed lake that connects to the ocean for several days or weeks each year when the barrier is breached by periodic flood events. This research suggests that those descriptions of Kirk & Launder (2000) and Hume et al. (2007) are not incorrect, however, are only applicable to limited phases of the evolutionary stages. Morphology of waituna-type lagoons is dynamic and prolonged barrier openings and estuarine phases can occur naturally. The openings are generally associated with high energy fluvial or marine forces but can also be caused or contributed to by sediment starvation (Forbes et al., 1995). The duration of barrier openings is dependent on the degree of barrier destruction and ability to recover. This research shows that, in Wainono and Te Waihora at least, the inlet/outlet may remain to expose the lagoon to tides for prolonged periods of time. Switching between the enclosed lake and estuarine conditions is a natural process that has occurred at waituna-type lagoons in the past before human intervention.

Above has an implication to classifications of coastal lagoons and estuaries. It is important to recognise the dynamics of coastal/rivermouth lagoons in classifications. Kain (2009) also found that Totara Lagoon on the West Coast demonstrates a transition between 'spit-lagoon' and ‘hapua-type lagoon’, related to the classification established by Hume and Herdendorf (1988). Morphological changes can lead a lagoon or estuary to a variation in typology. The users need to be aware of the limitations of each classification model as well as the purpose of classification.

6.3 Recent trends

Geomorphological changes at Wainono Lagoon in the decadal scale are discussed in this section along with an assessment of recent trends. The barrier morphology, sedimentation and lagoon size are the subject of discussion.

In this study, the barrier profile and aerial photograph analyses have established the landward movement of the backbarrier in the past 30+ years at the SCS5164 Wainono Hut, SCS5214 Wainono Lagoon and SCS5239 Wainono South survey sites. However, in contrast, the positions of the beach face appear to be characterised by progradation with the exception of SCS5214 Wainono Lagoon translating at a rate of 30 mm / year. It must be noted, however, that the progradation (+ 18 mm / year) at SCS5164 Wainono Hut may be a slightly biased result without the 1985 pre-storm data, predominantly showing the post-storm recovery. If the 1985 data are excluded, the trend at SCS5214 Wainono Lagoon is also characterised by progradation.

The results for SCS5214 Wainono Lagoon and SCS5239 Wainono South were congruent with Gabites’ (2012) who summarised the coastal changes in South Canterbury over the period 1986 to 2011. However, the results from this study for SCS5164 Wainono Hut differed from Gabites’ results. Over the period 1986 to 2011, the beach face at SCS5164 Wainono Hut translated at a rate of 20 mm / year (Gabites, 2012) whereas this study showed progradation at a rate of 18 mm / year over the period 1986 to 2014. The differing trends established by Gabites and by this study may result from the ‘sediment slugs’ (Neale, 1987) affecting the short term trends. These ‘sediment slugs’ are collective units of beach sediments that move along the South Canterbury coast, at a rate of approximately 1.4 km / year, and were discovered by Neale in 1987. This means, therefore, that the short-term trends are more susceptible to temporal fluctuations of the sediment budget than long-term trends.

According to Gabites (2012), the coast immediately north of Wainono Lagoon (at Hook Swamp Road and Hook Beach Road) is characterised by progradation. Conversely, the barrier adjacent to Wainono Lagoon (at SCS5164 Wainono Hut and SCS5214 Wainono Lagoon profile survey sites) is translating landward although the sediment volume is relatively stable. However, an approximately 1 km stretch south of the SCS5239 Wainono South survey site is again characterised by progradation. This section of the coast is where the artificial barrier construction took place after the 1985 storm. Further south, the stretch of coast where the Waihao Dead Arm runs along the coast to the Waihao Box is again characterised by landward translation of the barrier.

The beach accretion immediately north of Wainono Lagoon can be explained by the localised southerly longshore drifts hindering the northerly movement of sediments which generally occurs on the South Canterbury coast (Hewson, 1977). A long term trend, established by Hicks et al. (2006) for the period 1864 to 2004, was that the coast along Wainono Lagoon was relatively stable with accretion in most parts. However, because the profile at SCS5239 Wainono South was altered artificially, the trend at this site does not actually reflect the natural processes. A schematic summary of the longshore sediment transport and coastal changes over the period 1865 to 2014 at the Wainono Lowland coast has been developed and is shown- in Figure 6.2. The northern part of the Wainono Barrier is either stable or accreting due to the localised southerly longshore drifts. It is likely that the southern part of the Wainono Barrier is naturally translating at a relatively slow rate, however, this process is slowed down or altered by the artificial barrier beach reconstruction. The southern part of the barrier along the Waihao Dead Arm is also translating. This translation of the Waihao Dead Arm is important because it has implications for hazard management, which will be discussed in section 6.7.

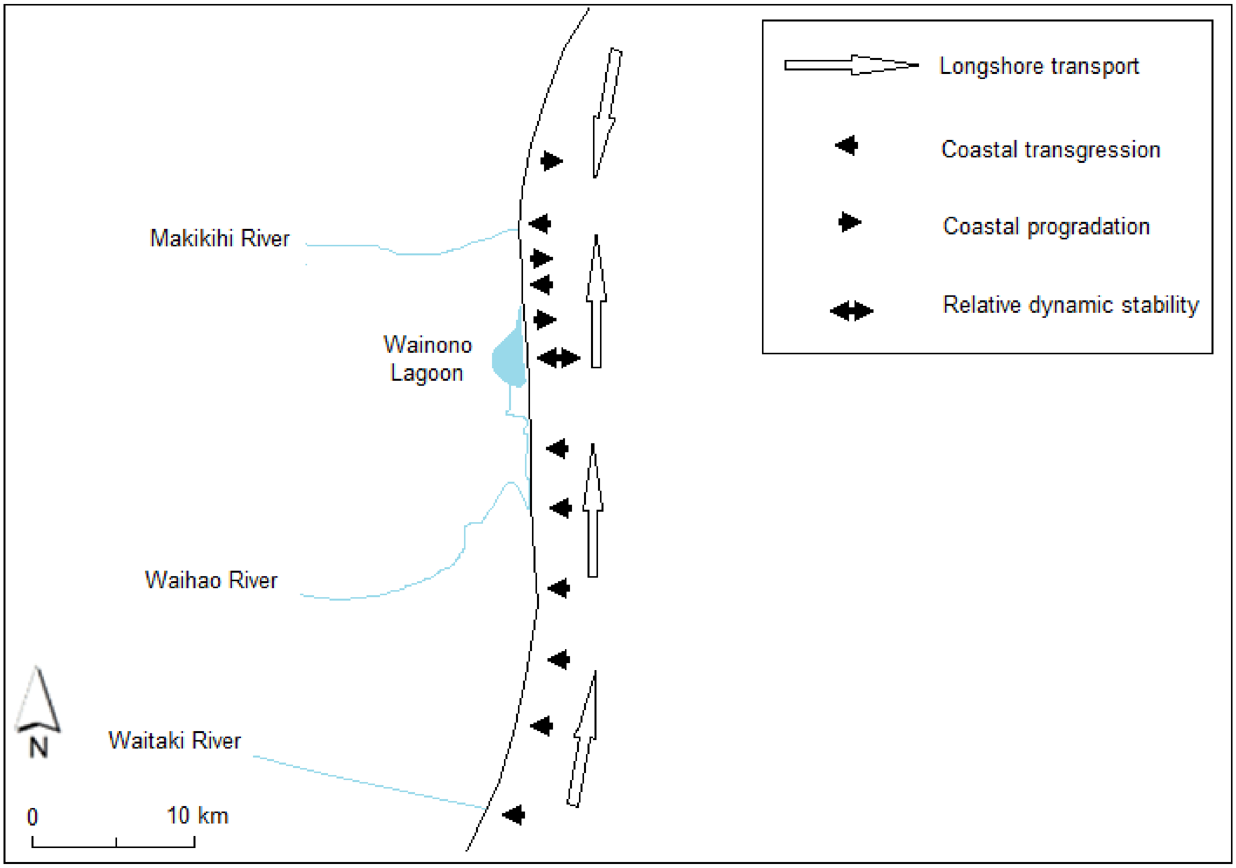


Figure 6.2. Net longshore sediment movement and coastal changes over the period 1865 - 2014. (Data based on the results of this study, Hewson, 1977; Hicks et al., 2006 and Gabites, 2012)

The aerial photograph analysis in this study revealed shrinkage in the Wainono Lagoon surface area during the period 1977 to 2009, however, this is most likely a short-term trend. A more recent satellite image from October 2015, which this study was unable to use for the quantitative GIS analysis, shows a higher water level and greater wetted perimeter compared to the 2009 image. It was reported that during the period 2007 to 2009, a long duration, moderate intensity drought occurred (A. Clark et al., 2011) and this would have lowered the water level in the lagoon. Fluctuation in the wetted perimeter occurs as a result of changes in water levels, which are affected by weather, irrigation in the catchment and connection to the sea. Dada et al. (2015), who studied the evolutionary trends of the Niger Delta shoreline over 100 years, found that the shoreline change strongly correlates with rainfall variability and river discharge. This correlation may also apply to the lagoonal shorelines at Wainono, however, the waituna-type lagoons are hydrologically more complex as the discharge is controlled by the barrier morphology and, at Wainono Lagoon, the artificial structure Waihao Box affects both the inflow and outflow. The Waihao Box can function as a tidal channel when it is open to the sea, which can cause fluctuations in the lagoon level (Pierce, 1980). In order to more fully assess changes and establish trends in lagoon shoreline and surface area, data over a longer period are required and it is recommended here that the regional council responsible for lagoon management keep monitoring the lagoon's beach profiles and collates aerial images, to this end.

This study found that sedimentation rates in Wainono Lagoon vary spatially and temporally. The rates of accumulation may be greater than 3 mm / year (Schallenberg & Saulnier-Talbot, 2015) in some areas. Lagoonal sedimentation is strongly linked with the land-use in the catchment. It is important to monitor the impacts of land-use change in order to avoid the accelerated sedimentation rates and undesirable infilling of waituna-type lagoons. In addition to the fluvial sediment input, the lagoon can receive a large amount of marine sediments during high energy events. While coring is useful to investigate the sedimentation rates of the past, repeated bathymetry surveys provide a comprehensive understanding of accumulation patterns in recent years. It is recommended that regional council responsible for lagoon management surveys the bathymetry of the lagoon regularly, monitors bathymetric changes and establishes the sedimentation rates and patterns. Sedimentation rates and patterns need to be considered as an essential aspect of sustainable lagoon management, which is also discussed further in section 6.7.

6.4 High energy events

It was discussed in Chapter 1 that storm events play a significant role in evolution of gravel dominated barriers. Short-term changes in barrier morphology, such as barrier roll-over and breaches, generally take place during high energy events (Orford & Carter, 1982; Pye & Blott, 2009). The findings of this study were congruent with above statement. It was also found that the significance of low frequency high energy events on the South Canterbury coast (Gerslov, 1991; Hewson, 1977) is not only relevant to erosion but also for the barrier morphology. The barrier profile analysis showed that major changes in barrier morphology at Wainono were caused by storm events. It is important to note that the impacts of high energy events in the morphology of gravel dominated coasts are often irreversible (unless artificial work is involved) in contrast to that of sandy coasts. Gravel coasts are reflective beaches which do not develop bar morphology (R. W. G. Carter & Orford, 1993) and aeolian sediment transport is negligible. While the storm profiles in sandy coasts can be seasonal, morphological changes associated high energy events on gravel dominated coasts can be permanent and result in evolution of the barrier.

The barrier side stratigraphy in this study did not show the typical lagoonal succession suggested by Boggs (2012) and Nichols (2009) that is characterised by mudstone with thin wave-rippled sand beds deposited by washovers. Evidence of barrier breach from 1985, 2001 and 2002 was not visually detected in the lagoon sediment cores. This means that evidence of storm-induced barrier breach is not always present or detectable in lagoon sediment cores. This also indicates that the sand layers present in the sediment cores in this study involved either significantly higher energy at the time of deposition or longer duration of high energy compared to the storm events recorded in 1985, 2001 and 2002.

Sediment analyses in this study identified two significant events of barrier breaching in cores WLB1 and WLB2. These events are particularly significant in terms of sediment deposition. One of them was an extreme event, depositing a large volume of coarse sediment over a short period of time, and the other suggests a switching to an estuarine condition over a prolonged period of time. Barrier breaches were inferred from anomalies in flow direction shown using AMS analysis of the cores. It is assumed these events are prior to the recorded breach events that occurred in 2002, 2001 and 1985 based on the sedimentation rate of 3 mm / year (Schallenberg & Saulnier-Talbot, 2015).

The direction of flow during the events of barrier breach was consistent. The AMS results showed that the flow was or initiated with a flow from the north. The breach site is likely to be north of the WLB1 and WLB2 sites. This is consistent with the approximate location of the barrier breach that occurred in July 2001 (Cope & Young, 2001) and known breach sites along the Wainono barrier (Stapleton, 2005). There is a possibility that breach repeatedly occurred at the same site/area.

The olive coloured sand layer at 20 - 40 cm dbs in WLB1 and 17.5 - 40 cm dbs in WLB2 is interpreted as a tsunami deposit. This interpretation itself needs to be discussed since it does not relate to other reliable contemporary observational records of tsunami waves in the area.

6.4.1 Tsunami deposit

The sediment analyses established that an extremely high energy event deposited a large volume of sediment in the barrier side of the lagoon. Extrapolation of time based on the sedimentation rate of 3 mm / year established by Schallenberg and Saulnier-Talbot (2015) suggests that this event occurred in the mid-20th century. Their Pb210 results from the core retrieved from the centre of Wainono Lagoon showed 14.25 cm dbs = 1963 and 20.75 cm dbs = 1945. The time of the event is estimated ignoring the spatial and temporal variation in sedimentation rates. The core sediment itself exhibits key features of a tsunami deposit which require more detailed discussion. This section provides the reasoning for the interpretation as well as for uncertainty.

The AMS analyses for the olive coloured sand section (20 - 40 cm dbs in WLB1 and 17.5 - 40 cm dbs in WLB2) suggests a single bed tsunami deposit which is characterised by a cycle of run-up and backwash. A distinction of single bed tsunami deposits from other deposits such as washover and storm deposits is challenging. The main difference between the tsunami and other waves is the wave length. Tsunami waves are characterised by an extremely large wave length and period, which generate the common features of tsunami deposits (Fujiwara, 2008).

A combination of sediment analyses in this study has established that a large volume of marine sediment was deposited by an extreme event. This extreme event, which was responsible for the sand layer 20 - 40 cm dbs in WLB1 and 17.5 - 40 cm dbs in WLB2, is thought to be the 1960 Chilean tsunami. The sediment layers exhibit the following characteristics of tsunami deposits:

- The flow pattern suggests a tsunami run-up and backwash.
- The run-up phase is characterised by gradual fining of sediments (Fujiwara, 2008)
- The backwash is characterised by a higher velocity. This feature is congruent with the characteristics of the 4,220 B.P. tsunami deposit found in Sumatra (Wassmer et al., 2015).

- It is marine sediment only found in the barrier side cores. Heavy rainfall associated with storm is unlikely.
- Bimodal sediment grain size distribution (K. J. Clark et al., 2015)
- Anomalous sedimentary features with coarse grain size (K. J. Clark et al., 2015; Takashimizu & Masuda, 2000)
- Intercalation of a sandy layer within a silt layer (Nanayama, 2008)
- The grain size distribution and AMS analyses in this study suggest that the backwash is characterised by a higher velocity. This feature is congruent with the characteristics of the 4220 B.P. tsunami deposit found in Sumatra (Wassmer et al., 2015).

While there is much evidence supporting hypothesis that this layer was deposited by the 1960 Chilean tsunami, there are also some gaps in this evidence associated with the lack of information. First, the AMS samples are assumed to represent the whole layer, despite the sample gaps. Core WLB2 has a maximum gap of 2 cm between samples. Core WLB1 presents larger gaps between samples. Second, mud-drapes which are a common feature of tsunami deposits (Fujiwara, 2008) were not clearly identified in core WLB1 and WLB2. Third, foraminifera was absent in this sandy section. The reason of the absence of foraminifera is unknown, however, dissolution of foraminifera is a possibility. If marine foraminiferal species were brought to the lagoon bed by high energy wave actions, there is a possibility that the tests dissolved over time due to the lower pH in the lagoon. Freshwater is more acidic with lower pH compared to the sea water. Regenberg, Schroder, Jonas, Woop, and Gorski (2013) conducted a dissolution experiment to study the dissolution process of foraminiferal calcite. Weak buffered acetic acid dissolved the tests of foraminifera over time and eventually completely disintegrated. This is a possible reason for the absence of foraminifera. However, the exact reason is unknown since marine foraminifera can be found in a waituna-type lagoon (K. J. Clark et al., 2015). Finally, there are no reliable records of the 1960 tsunami waves in the Wainono area. Information related to the 1960 tsunami is presented and discussed in below paragraph.

The record of tsunami waves and surges for the Wainono Lowland coastal area is still incomplete. Below is the data available to support the effects of tsunami and the possibility of barrier breach at Wainono Lagoon. On 22 May 1960, a tsunami was caused by a Chilean earthquake. A maximum height of 5.5 m at the Lyttelton Harbour was recorded (NIWA, 2013). At Timaru, 1.8 m fluctuations in water level were recorded and tsunami waves were recorded on 23 and 24 May (DTEC Consulting Ltd, 2001). Heavy surges were also recorded at the Oamaru Harbour. The estimated maximum height at Oamaru was 1.5 – 2.1 m (NIWA, n.d.). According to de Lange and Healy (1986), the estimated highest level above normal high tide at Lyttelton was 3.3 - 3.5 m and fluctuations of 0.9 - 2.8 m were recorded at Oamaru over 30 hours. Tsunami effects were recorded at major harbours both north and south of Wainono Lagoon. Although the tsunami effects at Wainono Lagoon were not documented, it is highly likely the Wainono Lowland coast experienced a tsunami wave and surges. It is possible that the sand deposit was a result of surges associated with the 1960 tsunami. The sediment analyses indicate a number of features of a tsunami deposit. However, further research and evidence is required to fully establish the case.

Other possible extreme events that could have caused the barrier breach in the mid- 20th century are as listed below.

1 Flooding on 20 and 22 February 1945. Torrential rainfall associated with a storm flooded many rivers in South Canterbury. Severe flooding of the Waihao River isolated Waimate for some time.
2 Flooding on April 1962. Extensive damage on Waihao Box, associated with flooding in South Canterbury, was reported (Cowie, 1957).
3 Cyclone Giselle (also known as Wahine Storm) on 9 April 1968. The lowland coast was flooded.

The reasons, why it is thought that the cause is most likely the 1960 tsunami, are the overwhelmingly higher energy involved in this event compared to the known storm events that caused a barrier breach, absence of this olive coloured layer in the cores WLW1 and WLW2 from the landward side of the lagoon as well as the key features of a tsunami deposit discussed earlier that this sediment layer exhibits.

6.5 Lagoon system

This section discusses and establishes the comprehension of the Wainono Lagoon system. Detailed information on the study area was presented in Chapter 2. The evolution and past behaviour of Wainono Lagoon was summarised earlier in this chapter. All the information is reviewed to understand the lagoon processes and to identify the key drivers that influence the lagoon system.

The history of Wainono Lagoon indicated that morphological evolution was caused by both natural processes and anthropogenic activities. Evolution in barrier morphology was triggered by high energy events and changes in sea level. The lagoon size and volume has been affected by modification of hydrology and changes in land-use. Human intervention is undeniably a significant component that has had impacts on the morphology, hydrology and ecology of Wainono Lagoon. It is essential to understand the components that affect the lagoon system in order to predict the future scenario of the lagoon and to develop a long-term management strategy.

The lagoon system is predominantly governed by coastal and fluvial processes. Atmospheric components are also interrelated, however, the focus of the discussion here is the coastal and fluvial influences as these components are more directly linked with anthropogenic activities. Comprehension of the coastal and fluvial influences is crucial in determining the lagoon morphology and long-term stability. A waituna-type lagoon is generally characterised by the fluvial inflow and outflow to the sea. However the barrier system is dynamic and inflow of marine water and sediments can occur. Figure 6.3 is a schematic summary of the Wainono Lagoon system with influencing factors. The lagoon system is directly influenced by fluvial and marine processes. The model is also applicable to other waituna-type lagoons.

The fluvial processes are responsible for the lagoon hydrology, morphology and ecology. They impact the lagoon system as an input. Water, nutrients and sediments enter the lagoon to influence the water level, water quality and sedimentation in the lagoon. The fluvial processes are susceptible to anthropogenic activities, which consequently affect the lagoon hydrology, morphology and ecology. The fluvial input is also affected by weather and water resource uses such as irrigation.

The primary components that are responsible for the barrier morphology are the sea level change, sediment budget and wave processes. While the wave processes have instantaneous influences on the beach/barrier morphology, the effects of changes in sea level and sediment budget show over a long term. Marine influences are most significant during extreme events with high energy waves. Consequently significant changes in the barrier morphology result from high energy events. Coastal processes are likely to be affected by both climate change and resource use/management which affect the sediment budget and coastal geomorphology.

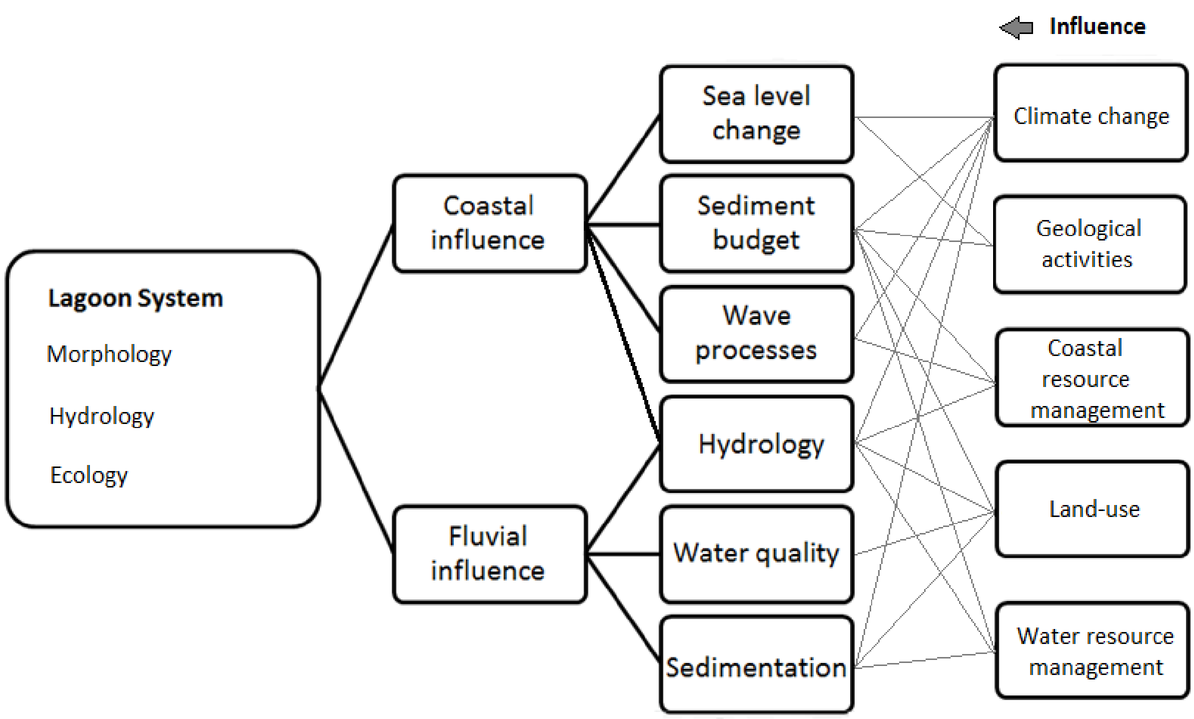


Figure 6.3. Schematic diagram of the Wainono Lagoon system with key influences.

At Wainono Lagoon, the sediment cores from the barrier side and the western side exhibited differing energy dynamics. The barrier side environment is very dynamic and prone to changes by marine processes. Significant changes can be caused by wave action during high energy events. Cores WLB1 and WLB2 contained sediment layers of olive coloured sand and black sand which were not present in WLW1 and WLW2. The greenish gray sand/silt layer and dark greenish gray silt layer in WLW1 (48.5 – 87 cm dbs) and WLW2 (7.5 – 57 cm dbs) were present in WLB1 (17-20 cm dbs, 40 – 46 cm dbs and 46 – 93 cm dbs) and WLB2 (15 – 17.5 cm dbs, 40 – 56 cm dbs and 56.2 – 92 cm dbs) with the modal grain size being slightly smaller. This means that cores WLB1 and WLB2 contained sediments derived from both fluvial and marine sources. On the other hand, the sediment analyses showed that the western side of the lagoon is dominated by fluvial processes. With an exception of the dark greenish gray fine sand at 48.5 – 54 cm dbs in WLW1 and the recent mud layer above 48.5 cm dbs in WLW1 and 20 cm dbs in WLW2 with high organic content, the modal grain size distribution in the whole core was relatively consistent. This shows that the energy environment was relatively stable at the WLW1 and WLW2 sites, with the layer of dark greenish gray fine sand indicating environmental changes in the lagoon catchment. Breaching of the barrier has been a natural and significant part of the lagoon history albeit one that occurs intermittently. Salinity was not ‘introduced’ by the construction of the Waihao Box, as suggested by Schallenberg and Saulnier-Talbot (2014), but rather its timescale of influence was extended. Salinity was also naturally present, to a smaller degree, due to regular storm wave overwashing, and rarely but very significantly, due to barrier breaching over the long term. The volume of marine deposition during the breach can also be considerable. The dynamic environment on the barrier side consequently influences the sedimentation and ecology in the lagoon as well as the barrier morphology.

6.6 Long-term stability status

This section assesses the long-term stability status of Wainono Lagoon. To predict the future scenario for Wainono Lagoon, an evolutionary model for waituna-type lagoons on a transgressive coast was developed.

On a geological time scale, coastal lagoons may be short-lived features as the general views suggest (e.g. Woodroffe, 2003). Kirk and Lauder (2000) argue that many of the barriers enclosing waituna-type lagoons are erosional and therefore they are ephemeral or disappearing features over hundreds or thousands of years. It needs to be acknowledged, however, many of waituna-type lagoons have been affected by anthropogenic impacts and resulted in a loss or shrinkage of the lagoon (Hemmingsen, 1997; Kirk & Lauder, 2000; Soons et al., 1997). Clearly, the stability status of coastal lagoons is largely influenced by human intervention. In this study, a theoretical framework has been applied to develop a model, which can be used to assess the long-term stability status of a waituna-type lagoon on a transgressive coast.

To date, there are no general schematic evolutionary models specifically developed for waituna-type lagoons. Type specific models are necessary to assess the long-term stability of a lagoon since there are no evolutionary models which apply to all lagoons (Cooper, 1994). The concept of long-term stability according to the relationship between the sedimentation and relative sea level rise was introduced in Chapter 1. Nichols' (1989, p.215) model introduced in Chapter 1 (Figure 1.4) does not differentiate the fluvial and marine deposited sediments despite they have differing impacts on the lagoon's stability. While fluvial sediments reduce the lagoon capacity, marine sediments primarily accrete the barrier beach and protect the lagoon from coastal erosion. Therefore Nicol's model has limited applicability to waituna-type lagoons where the balance between marine sediment budget and sea level rise governs the rate of barrier retreat. In this section, the concept of long-term stability of Nichol's is further developed to model the future scenarios for waituna-type lagoons. The model presented here has been developed accounting for the distinctive characteristics of waituna-type lagoons. The model is also applicable to enclosed coastal lagoons on a transgressive mixed sand and gravel coast elsewhere around the world.

Figure 6.4 shows the future scenarios of waituna-type lagoons, including Wainono Lagoon, on a transgressive coast. These scenarios have been developed based on the balance between sea level rise, sedimentation and barrier translation, using an understanding of past dynamics and evolution of several waituna-type lagoons, including Wainono, Te Waihora, Waimataitai, Washdyke and Waituna Lagoons. The long-term rates of barrier retreat are influenced by the sediment budget and sea level rise, as well as the overwash frequency and washover extent (Dolan & Godfrey, 1973) having an influence on the back barrier in particular. Three scenarios are described below.

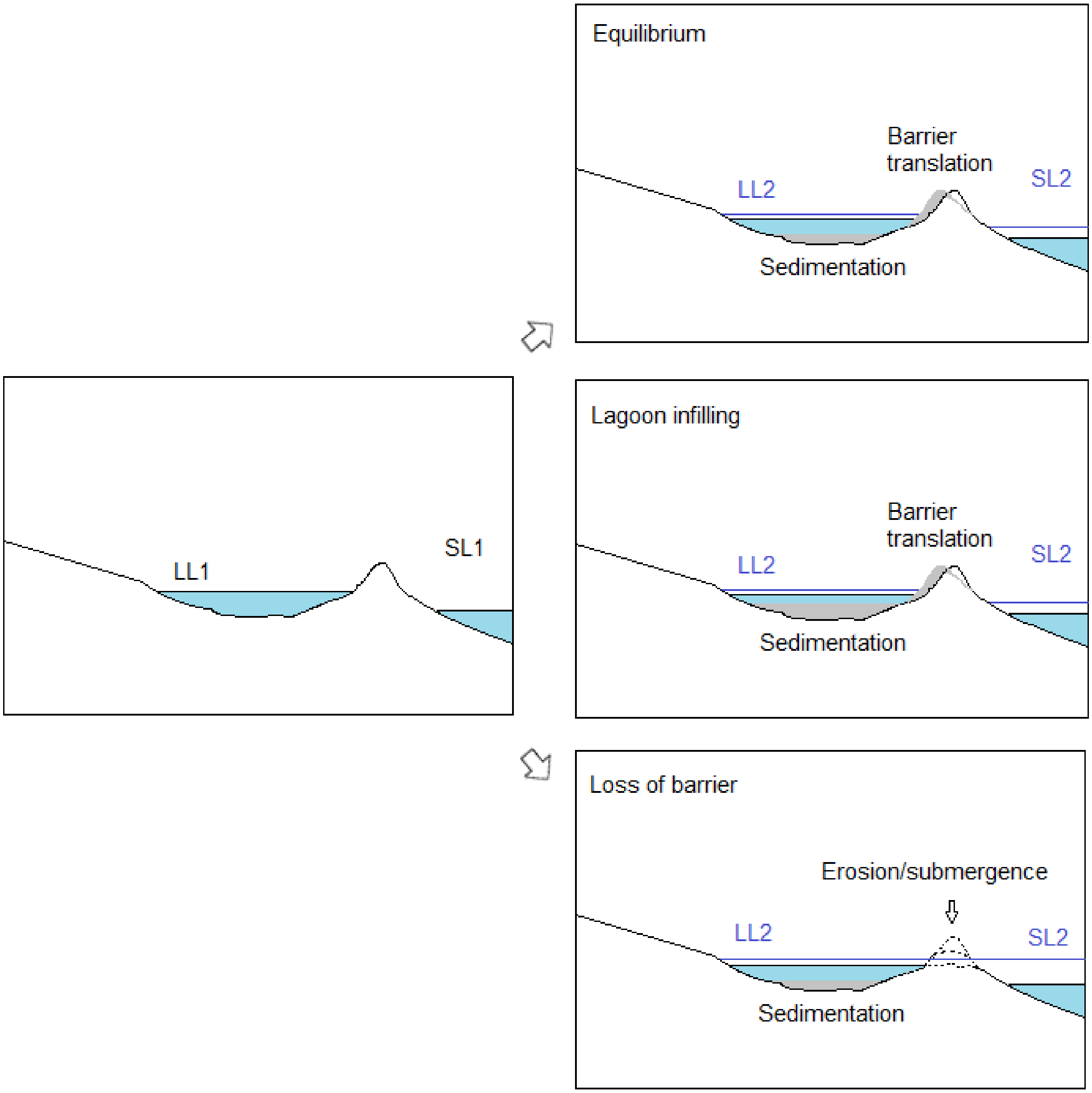


Figure 6.4. Evolutionary model for waituna-type lagoons on a transgressive coast. Waituna-type lagoons on a transgressive coast will either maintain an equilibrium state by inundation of surrounding land, or become filled with sediments, or lose the barrier to become partially or completely open to the sea.

Equilibrium state: For a waituna-type lagoon on a transgressive coast to persist, theoretically, the beach sediment influx needs to keep pace with the rate of sea level rise. In order to maintain the lagoon size, inundation of the surrounding land is inevitable. The whole lagoon retreats landward and the lagoon size may change depending on the geometry of the area. The geometry can also limit the eventual existence of the lagoon.

Lagoon infilling: A lagoon will shrink in size where the barrier translation or sedimentation in the lagoon occurs rapidly relative to the sea level rise. It is important to note that barrier roll-over results in increased rates of vertical sedimentation because the same volume of fluvial sediment is deposited in a smaller area (Adlam, 2014). For example, a process of infilling is occurring at Washdyke Lagoon where the barrier experiences erosional retreat. It is also important to note that barriers in rapid retreat (R. W. G. Carter et al., 1989) and narrowing barriers due to erosion (Masselink & Van Heteren, 2014) are also vulnerable to destruction. A loss of barrier can be triggered by a high energy event. A good example of this is Waimataitai Lagoon, where the barrier continued to retreat until the lagoon was completely lost by a barrier breach and destruction in 1933 (Kirk & Lauder, 2000).

Loss of barrier: This scenario will occur where marine deposits are unable to keep up with the rising sea level. The barrier will be eroded and eventually submerged or partially open to the sea. This is the predicted scenario for Te Waihora/Lake Ellesmere, where the southern part of the barrier is already eroding and narrowing (Hemmingsen, 1997; Kirk & Lauder, 2000). Once the barrier is permanently open or submerged, the lagoon will become an estuary or a bay.

Table 6.1 displays the rates of sea level rise, lagoonal sediment accumulation and barrier retreat, based on data available at present. Data from survey site SCS5214 Wainono Lagoon was chosen to calculate the rate of barrier retreat because the records from this site cover the longest period from 1985 to 2014 and data are not affected by artificial barrier beach reconstruction. As discussed earlier, the profile at SCS5239 Wainono South has been altered by artificial barrier beach reconstruction. It is suspected that the trend characterised by slight progradation trend at SCS5164 Wainono Hut is due to the 1985 pre-storm data being missing. For the SCS5164 Wainono Hut and SCS5214 Wainono Lagoon survey sites, if the 1985 data are not included, the beach face is characterised by progradation representing the recovery from the 1985 storm event

Table 6.1. Approximate rates of sea level rise, lagoon bed sedimentation and barrier translation. The rate of barrier translation was calculated based on the 1m AMSL back-barrier position at profile survey sites along Wainono Lagoon.

Processes	Rates
Relative sea level rise (New Zealand)	1.7 mm/year (Hannah & Bell, 2012)
Lagoonal sediment accumulation	3 mm/year (Schallenberg & Saulnier-Talbot, 2015)
Back barrier retreat	520 mm/year (SCS5214 Wainono Lagoon, 1985-2014)
Beach face retreat	30 mm/year (SCS5214 Wainono Lagoon, 1985-2014)

which is somewhat biased. Therefore the pre-storm data from 1985 are included in the calculation of rates of barrier retreat. According to the data presented in Table 6.1, the sediment accumulation rate is greater than the rate of sea level rise. This indicates that, unless the sediment accumulation rate is reduced, Wainono Lagoon will face shrinkage in lagoon size in the future. This represents the surplus lagoon in Nichols' (1989) model (Figure 1.4).

Barrier translation will accelerate the process of lagoon shrinkage. The recent changes in the south-eastern section of the lagoon bed (Figure 4.2b-c) show that the sedimentation between 2002 and 2015 spatially varied from -200 mm to 400 mm with the maximum accumulation rate of >30 mm per year. Closer monitoring and a better understanding of sedimentation are required in order to comprehend the sediment accumulation processes in the lagoon.

It is important to note that rates of barrier translation may be increased by the acceleration of rising sea level in the future. Although Hannah (2004) concluded that acceleration in the sea level rise in New Zealand was not detected over the 20th century, the study of Church and White (2011) show that the global rate of sea level rise has increased since 1961. The linear trend shows a rate of 1.7 mm / year for the 1900 to 2009 period whereas the rate is 1.9 mm / year since 1961. While uncertainty remains in projecting the future trend, accelerated rates of sea level rise are anticipated for the 21st century (Church et al., 2013).

6.7 Management

Locally and globally, management of a lagoon is of high public and scientific interest which requires addressing of various issues such as degradation of water quality, loss of ecological and economic values, loss of land associated with shoreline retreat and risk of inundation (e.g. Gonenc & Wolflin, 2005; Philomena, 1994; Pye & Blott, 2009). Comprehension of the lagoon system and long-term stability discussed earlier are directly relevant to and provide a basis for policy making and the management of coastal lagoons. In this section, potential management strategies for Wainono Lagoon and their effects are explored.

Wainono Lagoon has been, and will continue to be, affected by anthropogenic activities including management interventions. The management in the early European history focused on the lagoon level in order to increase the land available for agricultural use. The lagoon size was significantly reduced since the drainage of the wetland and construction of the artificial outlet to the sea. Today, as a regional and national significance, Wainono Lagoon represents a high degree of management intervention involving artificial barrier reconstruction and a restoration project concerning the water quality issue. However, despite its importance for sustainable lagoon management, consideration of the lagoon morphology and long-term stability appears to have been negligible in the decision making processes to date. This is because there was limited or no information available regarding the future scenario of Wainono Lagoon morphology in the past. In fact, geomorphological changes in the coastal environments associated with sea level rise (e.g. Figure 1.3) are poorly understood in general (Pethick, 2001). This study established that the future scenario of Wainono Lagoon is ‘infilling with sediments’ if the current trends in sedimentation, sea level rise and barrier roll-over continue. In reality, however, coastal processes are not characterised by linear trends (Masselink & Hughes, 2003; Pethick, 2001) and therefore it is dangerous to predict long-term trends based on the assumption that the short-term trends will persist. Acceleration of sea level rise (Church et al., 2013) and increased frequency and intensity of storms associated with climate change (Ministry for the Environment, n.d.-a) are anticipated in the future yet projection of trends is difficult as uncertainty remains. Management strategies for Wainono Lagoon need to be developed based on a good comprehension of the lagoon system and regular monitoring of environment and geomorphology.

The key issues which need to be addressed at Wainono Lagoon at present are as identified below.

- The degradation of water quality and ecosystem (Environment Canterbury, 2008, 2012)
- Flooding risk associated with the blockage of the Waihao Dead Arm (Gabites, 2012; Pemberton, 1980)
- Sea water inundation risk associated with barrier breach (Stapleton, 2005)
- Sedimentation rates being greater than the rate of sea level rise

Sea level rise is a crucial component in coastal and lagoon management today. Data show that some parts of the Wainono Lowland coast are translating although the stretch adjacent to the lagoon is relatively stable. In theory, the rising sea level will result in translation of the Wainono barrier over a long-term. Issues associated with the barrier translation are ultimately a matter of response to the threat of sea level rise. Management of Wainono Lagoon must incorporate the effects of the sea level rise.

Increased inundation risk associated with sea level rise and erosion is an international issue (Nicholls & Cazenave, 2010). Generally the sea level rise risk mitigation policies can be divided into three categories: protection, accommodation and retreat (e.g. Abel et al., 2011). Internationally there is a shift in management approach from hard-protection measures characterised by engineered structures to soft-protection measures such as artificial redistribution of sediments. In New Zealand, it is also increasingly recognised that protection works are not environmentally sustainable, reliable nor economically effective in the long-term considering climate change (Ministry for the Environment, 2009). The management of the Wainono barrier in the last few decades represents the soft-protection approach, such as the artificial barrier reconstruction and dredging of the Waihao Dead Arm. Currently an alignment of the Waihao Dead Arm is considered as a measure to address the blockage issue according to Gabites (2012). Below sections discuss the short to medium-term management strategies and long-term management strategies.

6.7.1 Management framework

In New Zealand, the Resource Management Act (RMA) of 1991 is the overarching legislation for environmental and resource management. The RMA (1991) was introduced to assimilate and replace more than 40 existing pieces of legislation associated with environmental management. Under the RMA (1991), national policy statements, including the New Zealand Coastal Policy Statement (NZCPS), are mandated. NZCPS (2010) provides direction to the local government authorities on strategic coastal planning. In New Zealand, the Treaty of Waitangi confirms and guarantees the customary rights of tangata whenua (indigenous people of New Zealand). Section 8 of the RMA (1991) requires that the principles of the Treaty of Waitangi are taken into account by all persons exercising functions and powers under the act. Iwi Management Plans have been prepared by local tribes and sub tribes to express cultural values associated with resource and environmental management.

In Canterbury, the Environment Canterbury Regional Council (ECAN) is responsible for the development and implementation of the regional policy statements and plans, including a regional coastal plan (Figure 6.5). For Wainono Lagoon, while ECAN is the principal manager of the natural resources in the adjacent coastal area and the catchment of the lagoon, the local community and other stakeholders are heavily involved in the management of the lagoon and its feeder catchment. The Canterbury Water Management Strategy (CWMS) was introduced to provide a collaborative framework for the management of water resources in Canterbury. Following that, zone committees, consisting of community members, local rūnanga and council representatives, started to form in 2010. Ten zone committees are responsible for the development and implementation of water management programmes to meet their targets. Wainono Lagoon falls under the Lower Waitaki Zone and its significance is acknowledged in the programme. A restoration project, involving numerous organisations and the local community, aims for the improved water quality, biodiversity, cultural valued and amenity values attached to Wainono Lagoon.

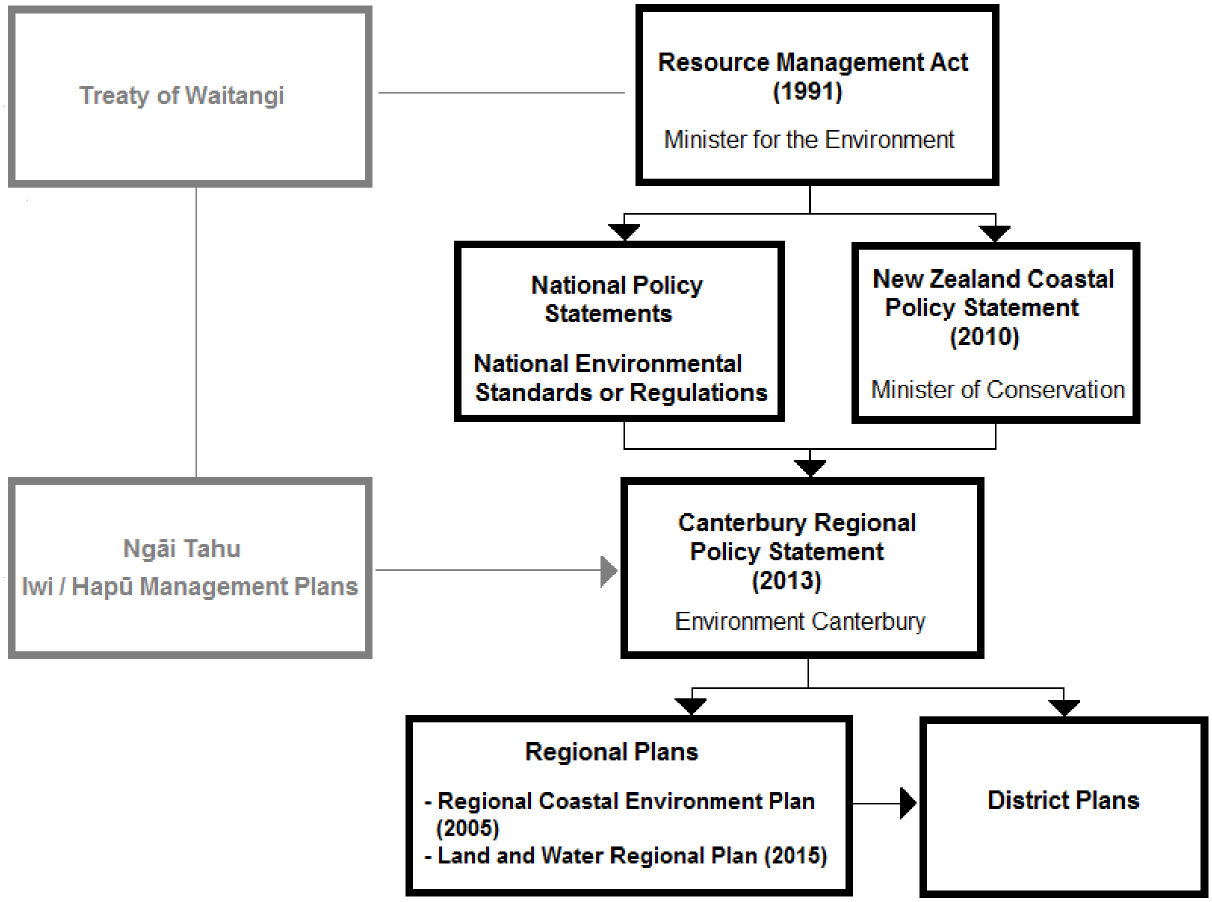


Figure 6.5. Schematic summary of the management framework for coastal lagoons in Canterbury.

6.7.2 Short to medium-term management strategy

Artificial barrier reconstruction of the Wainono barrier and mechanical dredging or alignment of the Waihao Dead Arm is considered short to medium-term management strategy. These are the measures that have been taken and/or considered to address the undesirable effects of overwash and barrier breach. It is possible to reduce the vulnerability of the Wainono barrier to avoid destruction and maintain the lagoon by artificially reconstructing the barrier. With this approach, it is essential to understand the sediment movements associated with overtopping and overwash in order to achieve the desired management outcome.

Overtopping is characterised by a negative feedback where as overwash represents a positive feedback in the wave action and barrier response relationship (Matias et al., 2012). Overtopping steepens the beach face and raises the barrier crest which increases potential for overwash while limiting potential for further overtopping. The June 1985 profile in Figure 4.5 (section 4.3) displays a high barrier crest with steep beach face which has been worked by previous high energy waves. This created a setup which is prone to overwash. Similarly, artificial narrowing of a barrier by raising the barrier crest increases its vulnerability to overwash and barrier breach. If a barrier breach is undesirable, the artificial barrier reconstruction must provide a buffer to allow overtopping and energy dissipation prior to extreme events which may involve frequent monitoring and maintenance of the barrier.

While this approach reduces the immediate risk of blockage and sea water inundation, it does not address the lagoonal sediment infilling and risks associated with the sea level rise in a long-term. The inundation risks would only increase as the sea level rises and the barrier migrates closer to the land which is already at risk.

6.7.3 Long-term management strategy

This section introduces and explores an option of managed retreat as a long-term approach. A long-term management policy at Wainono Lagoon needs to incorporate key values associated with the lagoon. The Lower Waitaki Zone Implementation Programme outlines the improved ecosystem of Wainono Lagoon as a primary objective. The issue of sea water inundation risk for the surrounding agricultural land also needs to be addressed. This issue is anticipated to be increasingly challenging as the sea level continues rise. The engineering solution may no longer be a sustainable option in the future if the coastal retreat persists. The New Zealand Coastal Policy Statement outlines that local government must give consideration to the relocation of the coastal community in extreme circumstances for areas prone to coastal hazards over the next century (Department of Conservation, 2010). Wainono is currently not in an extreme situation, however, coastal retreat is evident and the lagoon shrinkage is inevitable over a long-term unless landward retreat of the lagoon is enabled.

A potential long-term approach, which is considered environmentally viable for Wainono Lagoon, is the “managed retreat behind ecological defence” (Abel et al., 2011). This approach is centred on the environmental sustainability, conservation values and economic benefits. It is important to note that the perception of the local community has not been taken into consideration as it is beyond the scope of this study. The environmental effects of the managed retreat behind ecological defence are discussed and explored below.

Managed retreat behind ecological defence is a hazard management approach which involves the “withdrawal, relocation or abandonment of private or public assets” (Vandenbeld & Macdonald, 2013, p. 161) to allow invasion and/or retreat of coastal ecological protection, such as wetland and saltmarsh. One of the first managed retreat examples in the UK was at Tollesbury (in Black Estuary), Essex. Agricultural land was returned to intertidal habitat after the removal of sea wall defence. Managed retreat is increasingly considered as a more cost effective and sustainable method of coastal protection (Garbutt, Reading, Wolters, Gray, & Rothery, 2006). This method is also beneficial in terms of conservation and biodiversity which is legally recognised under the European Union Habitats Directive (C.E.G., 1992).

In New Zealand, preservation and protection of the natural character of coastal environments, wetlands, lakes, rivers and their margins, is acknowledged by Section 6 of the RMA (1991). Waituna-type lagoons are internationally rare (Kirk & Lauder, 2000) and the significance of Wainono Lagoon is recognised regionally and nationally (Environment Canterbury, 2012; Ministry for the Environment, n.d.-b). Waimataitai Lagoon and Washdyke Lagoon in Timaru are good examples of waituna-type lagoon where human intervention resulted in the complete or partial loss of the lagoon system. At Wainono Lagoon, degradation or loss of the lagoon by the future management intervention may be considered contrary to the Section 6 of the RMA (1991). The approach of managed retreat behind ecological defence at Wainono Lagoon will involve the natural barrier retreat, consequent inundation of the surrounding land and invasion/retreat of the wetland into the agricultural land. The Waihao Dead Arm will be blocked by the washover material and the lagoon will lose its connection to its outlet to the sea. The lagoon level will consequently rise and inundate the surrounding land. This approach ultimately is to return the reclaimed land to the original state of lagoon/wetland complex. The benefit and rationale of this approach is the restoration and continued existence of Wainono Lagoon while providing a natural coastal defence and habitats for plants and animals without ongoing maintenance costs in the future. The disadvantages are associated with the loss of agricultural land and potential effects on infrastructure such as the railway and road in vicinity of the lagoon, however, the degree of development and population density in the area is relatively low. Anticipated difficulties of this approach include engagement with the local community addressing uncertainty of sea level rise effects and time frame.

Management of Wainono Lagoon will be increasingly challenging in the future with expected sea level rise, climate change and increased demand for resource use and development. Maintaining of the existence of Wainono Lagoon and minimisation of coastal hazard can be achieved, if the effects of sea level rise and sacrifice of coastal land are accepted. Barrier translation is the geomorphological response of Wainono Lagoon to the sea level rise. The shrinkage of the lagoon may be accelerated by high lagoonal sedimentation rates. If the management aims the long-term stability and existence of the lagoon, it needs to be recognised that Wainono Lagoon will need to migrate landward to maintain its existence and it will likely involve blockage of the Waihao Dead Arm. It is essential that management of Wainono Lagoon integrates conservation and coastal hazard management.

6.8 Summary

This chapter presented detailed discussions on the inferred history of Wainono Lagoon and recent trends. Relevant concepts in lagoon morphology were revisited and their implication and management options were discussed. In this section, each research objective and research question is addressed.

The research objectives which are listed below have been attained.

Objective 1: Reconstruct a history of the lagoon environment and morphological evolution over the historical time was achieved in section 6.2.

Objective 2: Components that influence the lagoon system and morphology were identified in section 6.5.

Objective3: The long-term stability of Wainono Lagoon was assessed in section 6.6.

Objective 4: An evolutionary model for waituna-type lagoons was developed in section 6.6.

Finally, the research questions that were stated in Chapter 1 are answered.

Question 1: What has been the evolutionary history of Wainono Lagoon in the last 300 years?

As illustrated in section 6.2, Wainono Lagoon was in an estuarine condition approximately 300 years ago. There was at least one inlet along the barrier and the lagoon was exposed to tides. The Wainono barrier eventually redeveloped and the lagoon was enclosed again. Wainono Lagoon was in a freshwater-dominated environment surrounded by extensive wetlands. After the arrival of the Europeans, a large part of the wetland was drained and an artificial connection to the sea (the Waihao Box) was formed. As a result, the lagoon size was significantly reduced. High energy events play an important role in morphology and evolution of the barrier. Overwash and barrier breach also result in increased salinity in the lagoon as well as deposition of marine sediments within the lagoon. Despite the rising sea level and seaward migration of the backbarrier, translation of the barrier was not evident over the past 30 years.

Question2: What are the causes of environmental changes in the lagoon?

Environmental changes at Wainono Lagoon were often associated with changes in the barrier morphology and lagoon hydrology. These were caused by both anthropogenic activities and natural processes including high energy events and sea level rise. This study found that barrier openings and reestablishment had considerable impacts on salinity and ecology in the lagoon. Artificial alteration in hydrology and changes in land-use in the catchment also had significant impacts on the lagoon environment.

Question3: How did the bathymetry of the lagoon change in the recent years and what is the implication?

The recent changes in bathymetry displayed a significant spatial variation. Sediment core analyses also revealed temporal variation in sedimentation with marine influences. This study found that resuspension and redistribution of sediments occur at Wainono Lagoon and the bed elevation range was decreased by preferred deposition in depressions over time. Sediment accumulation rates calculated from a sediment core does not represent the sedimentation rate of the whole lagoon. Monitoring of bathymetry change and sedimentation pattern is crucial in lagoon management and prediction of its geomorphological state in the future.

Question 4: Have there been changes in the position of the lagoon shoreline in the recent decades?

The aerial photographs displayed changes in the position of the lagoon shoreline. A trend was not established based on four aerial images because the lagoon levels fluctuate based on the weather and tides. This highlights that the lagoon morphology is susceptible to the changes in hydrology in the catchment. Due to the variables such as weather and irrigation, a longer time frame is necessary in order to establish a trend in movement of the lagoon shoreline.

Question 5: What is the geomorphic state of Wainono Lagoon likely to be in the future?

Based on the current management and recent data, it is likely Wainono Lagoon will be filled with sediments over time. Despite the chronic erosion of the Canterbury Bight, the shoreline adjacent to Wainono Lagoon appears to be relatively stable. The coast between the mouth of Waimate Creek and the Waihao Box appears to be translating. This landward migration of the shoreline will naturally result in the blockage of the Waihao Dead Arm and increased lagoon size by inundation of surrounding land. However, this natural process will highly likely be interfered by flood hazard management such as realignment of the

Waihao Dead Arm. Hazard management can act as a hindrance to Wainono Lagoon taking its natural evolutionary course and lagoon's long-term stability.

Chapter 7. Conclusion

7.1 Thesis findings

The morphology of waituna-type lagoon is dynamic perhaps even more so than appreciated in most previous research on the present day morphology (e.g.Kirk & Lauder, 2000; Stapleton, 2005). Prolonged barrier openings and estuarine phases do naturally occur under the influence of high energy conditions or sediment starvation. This study found that Wainono Lagoon has been in an estuarine phase for a prolonged period of time at least once since the closure of the barrier. Evolution of waituna-type lagoons are the result of morphological changes in response to environmental changes including sea level rise, high energy events, climate change and anthropogenic activities.

Wainono Lagoon is a waituna-type lagoon on a transgressive coast. Today, despite the chronic erosion of the Canterbury Bight, the coast adjacent to Wainono Lagoon is relatively stable, with very slow translation of the southern part of the Wainono barrier. The lagoonal sedimentation rates are high relative to the rate of sea level rise, which means that, if the current trends continue, the lagoon will become filled with sediments over time. This highlights the necessity of monitoring of the sedimentation regime in the lagoon, which is hardly understood at present. Translation of the barrier further south along the Waihao Dead Arm will cause blockages and the management of this issue will also affect the future stability of Wainono Lagoon.

Management intervention can result in accommodation or hindrance in the natural evolution of waituna-type lagoons. At Wainono Lagoon, inadequate understanding of human impacts on the lagoon's geomorphology and a lack of adequate strategy may result in accelerated infilling of the lagoon. In development of a long-term policy and management strategies, it is critical that the morphological evolution and long-term stability status is taken into consideration in order to avoid undesirable outcomes, such as human induced infilling of the lagoon. This study provides a better understanding of the dynamics of Wainono Lagoon as a basis for development of such management policy and strategies.

7.2 Evaluation of this research

The primary purpose of this study was to establish the past behaviour of Wainono Lagoon in order to comprehend the lagoon system and to predict future scenarios. This purpose has been fulfilled by successfully achieving the four research objectives: (i) reconstruction of the evolutionary and environmental history of Wainono Lagoon, (ii) establishment of the lagoon system and its driving forces, (iii) assessment of the long-term stability and (vi) establishment of the general evolutionary model for waituna-type lagoons.

In addition to achieving the research objectives, this thesis has made significant contributions to existing theories of dynamics and evolution of waituna-type lagoons. First, this study of Wainono Lagoon has provided an example that supports the existing theory. This thesis provides a case study of a mixed sand and gravel coastal lagoon to which could be applied the evolutionary theory of Forbes et al. (1995), based on coarse clastic barriers. Second, this study also highlighted some theoretical limitations and developed a new model. It was realised the existing long-term stability model of Nichols' (1989) did not differentiate fluvial and marine sedimentation, and its applicability to diverse types of lagoons was limited. In order to assess the long term stability of Wainono Lagoon, a model accounting for the distinctive characteristics of waituna-type lagoons on a transgressive coast was necessary. This issue was resolved by developing a new evolutionary model specifically designed for predicting the future of waituna-type lagoons. This is a significant contribution both nationally and internationally because waituna-type lagoons are common in New Zealand and the model could be applicable to barrier enclosed lagoons on transgressive gravel dominated or coarse clastic coasts elsewhere in the world. Third, this thesis presents a new perspective on the definition of waituna-type lagoons. The finding that the estuarine phases occur added an insight that waituna-type lagoons can switch between enclosed lagoon and estuarine conditions in addition to the currently known status as an enclosed lagoon with occasional openings.

This study also has limitations. The timeframe covered by this study was limited by the specific requirements of the AMS technique and availability of suitable coring instruments. The dates of events are also unknown. Two samples from core WLB2 have been sent to a research laboratory for radio carbon dating but the results have not been received to date. Nevertheless, significant evolutionary and environmental changes were inferred from the sediment analyses. The combination of techniques used in this study increased the robustness of inferences and successfully established the past environment, hydrodynamic conditions and events of barrier breach.

Herein AMS was used for the first time in a lagoon study in New Zealand. The use of AMS in this research, in conjunction with sediment characteristics and foraminiferal analyses, enabled inferences of anomalies in sediment deposition. AMS is useful in identifying barrier breaches. The limitation is that AMS cannot be used to analyse sediment layers which are less than 2 cm in depth, which may include many of the deposits by short-term breach events. Limitation is also posed by the sediment grain size that is suitable for the AMS analysis. The ability to infer avulsions of major rivers into waituna-type lagoons by investigating the palaeocurrents and past hydrodynamic conditions using AMS is limited due to the nature of the gravel dominated sediment. Other challenges included retrieving sediment cores that were long enough to cover the desired time frame without disturbing the orientation of sediment grains.

7.3 Suggestion for future research

The formation of the Wainono barrier remains unclear and much longer cores will be required to investigate its origins and evolutionary history. For example, core lengths of 15.7 m and 9.5 m were required to cover the Holocene history of Te Waihora/Lake Ellesmere (Soons et al., 1997). At Wainono, further investigation into the deeper section (below 92 cm dbs) of the barrier side bed will also confirm the time period of the tidal phase and possibly the cause of the long-term barrier opening. However, as discussed in Chapter 3, it is challenging to use the AMS techniques with a coring technique that can retrieve such long cores. For example, vibro-coring, a coring technique which would enable the retrieval of long cores, would disturb the orientation of the sediment grains and thus not suitable for the AMS analysis. While the AMS analysis is useful to infer the past barrier openings and hydrodynamics, the formation of the coastal barrier can be investigated with other analyses. J. B. Jensen and Stecher (1992), for example, used seismic sequence analytical methods in conjunction with sediment analyses including pollen analysis and radio carbon dating to investigate the Paraglacial barrier-lagoon development in the Baltic Ice Lake in south-western Baltic. They successfully inferred the evolutionary history of the barrier-lagoon in the late Pleistocene and Holocene. Using the seismic sequence analysis with sediment analysis used in this study would enable the reconstruction of the full Holocene evolutionary history of Wainono Lagoon and its barrier.

This study found that Wainono Lagoon experienced an estuarine phase at least once since the closure of its barrier. While waituna-type lagoons are known as 'enclosed' coastal lakes today, it is established that at least Te Waihora (Hemmingsen, 1997; Soons et al., 1997) and Wainono Lagoon have experienced long-term barrier openings. Currently it is unknown whether other waituna-type lagoons have switched to estuarine conditions in their evolutionary history. A study involving a suite of coring from multiple waituna-type lagoons would be useful to further develop our knowledge of the morphological evolution of lagoons of this type.

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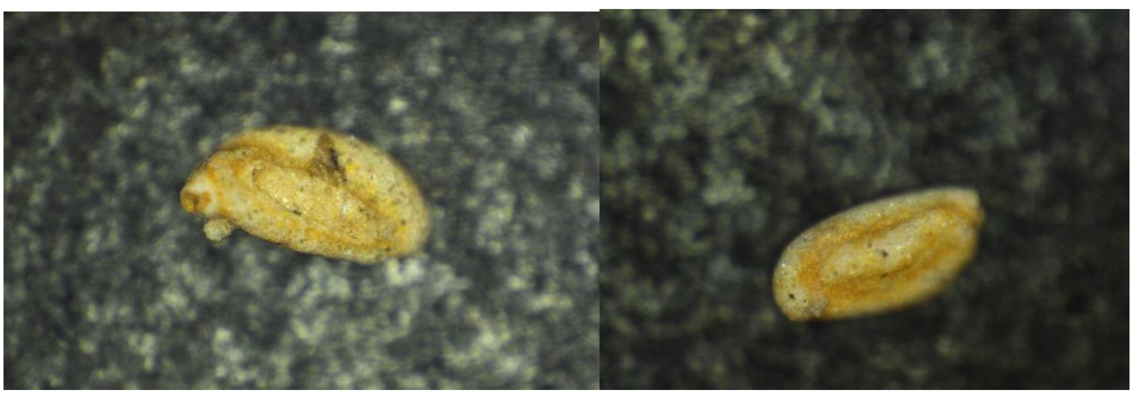
Appendices

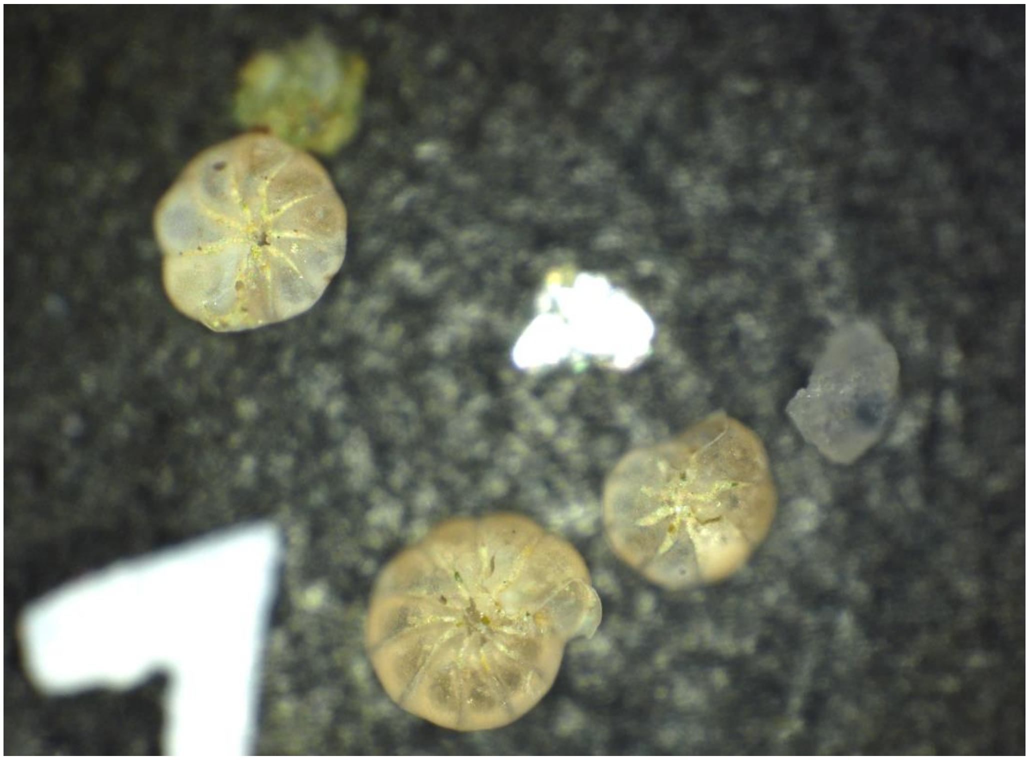
Appendix 1

Foraminifera

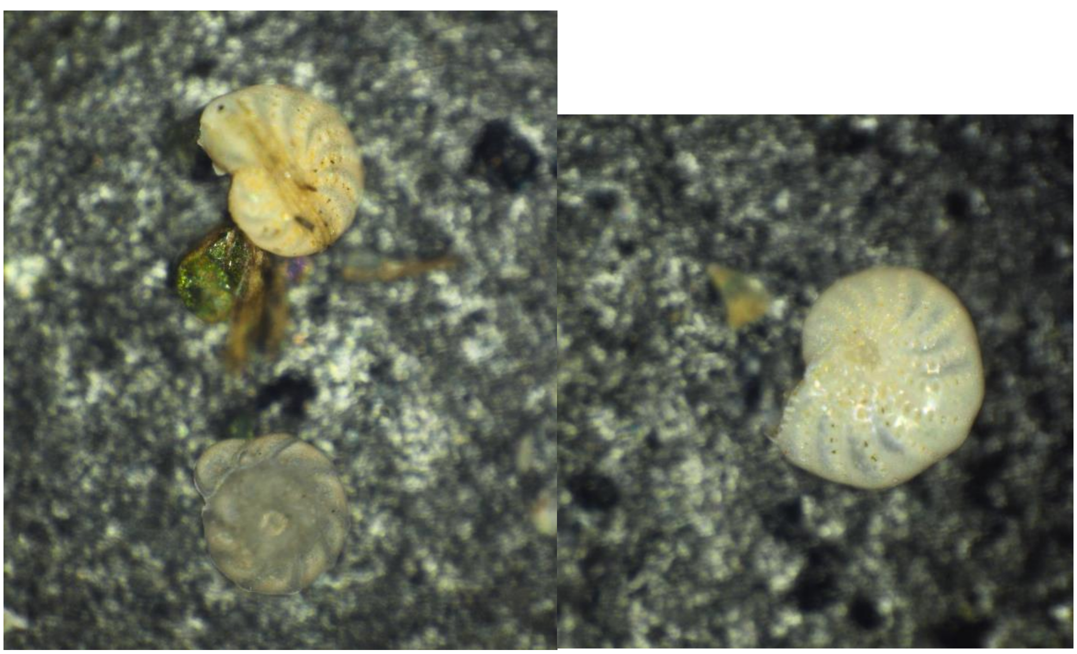
Trochamminita salsa



Miliammina fusca



Ammonia parkinsoniana



Elphidium advenum

Appendix 2

Authorisation to take sediment cores from Wainono Lagoon

Department of Conservation
Te Papa Atawhai

File Ref: NHS-12-11

14 May 2015

Maki Norman
223 Condell Avenue
Papanui
Christchurch 8053

Dear Maki

Re: RESEARCH & COLLECTION AUTHORISATION 42083-GEO APPROVAL

I am pleased to advise you that your application for a Research and Collection authorisation has been approved and I am now able to offer you an authority outlining the terms and conditions of this approval. Please find the authority enclosed.

This document contains all the terms and conditions of your authorisation to undertake the activity and represents the formal approval from the Department for Maki Norman, to carry out the activity.

Please read the terms carefully so that you clearly understand your obligations.

Yours sincerely

S Jones

Sally Jones
Conservation Partnerships Manager
South Canterbury District

South Canterbury District Office
Private Bag, Wairepo Road, Twizel 7944, New Zealand
Telephone 03-435 0802, Fax 03-435 0852

DOCDM-1600470

Department of Conservation
Te Papa Atawhai

Authority for research and collection on public conservation land

Authorisation Number: 42983-GEO

THIS AUTHORITY is made this 14th day of May 2015

PARTIES:

The Minister of Conservation (the Grantor)

AND

Maki Norman (the Authority Holder)

BACKGROUND:

A. The Director General of Conservation is empowered to issue authorisations under the Conservation Act 1987, the National Parks Act 1980 the Reserves Act 1977 and the Wildlife Act 1953 (the Conservation Legislation).

B. The Authority Holder wishes to exercise the authorisation issued under the Conservation Legislation subject to the terms and conditions of this authority.

OPERATIVE PARTS:

In exercise of the Grantor's powers under the Conservation Legislation the Grantor **AUTHORISES** the Authority Holder under the Conservation Legislation together with the right to exercise this Authority on the Land subject to the terms and conditions contained in this Authority and its Schedules.

SJones

SIGNED on behalf of the Director-General of Conservation
by Sally Jones acting under delegated authority
in the presence of:

Chris Coulter
Witness Signature

Witness Name: Chris Coulter

Witness Occupation: Ranger Partnerships

Witness Address: 32 George St Geraldine

A copy of the Instrument of Delegation may be inspected at the Director-General's office at 18-22 Manners Street, Wellington.

1

SCHEDULE 1

1.	**Authorised activity (including approved quantities of material and collection methods).** (clause 2)	**A. Activity** - to collect sediment core samples for research purposes **B. Quantity** – up to 4 samples being 50 millimeters in diameter and up to a maximum of 3 metres long **C. Methods** - i. samples shall be collected using a piston corer or percussion corer ii. all samples shall be collected up to 3 meters from the bed of the Wainono Lagoon
2.	**The Land** (clause 2)	The Wainono Lagoon, Wainono Lagoon Conservation Area
3.	**Authorised Personnel** (clause 3)	a. Maki Norman b. Nick Key
4.	**Term** (clause 4)	Commencing on and including 11 May 2015 and ending on and including 30 June 2016
5.	**Authority Holder's address for notices** (clause 10)	The Authority Holder's address in New Zealand is: 223 Condell Avenue Papanui Christchurch 8053 Phone: (03) 930-0104 Email: maki.norman@pg.canterbury.ac.nz
		The Grantor's address is: Level 4 73 Rostrevor Street Hamilton 3240

SCHEDULE 2

STANDARD TERMS AND CONDITIONS OF THE AUTHORITY

1. Interpretation

1.1 The Authority Holder is responsible for the acts and omissions of its employees, contractors or, agents. The Authority Holder is liable under this Authority for any breach of the terms of the Authority by its employees, contractors or agents as if the breach had been committed by the Authority Holder.

1.2 Where obligations bind more than one person, those obligations bind those persons jointly and separately.

2. What is being authorised?

2.1 The Authority Holder is only allowed to carry out the Authorised Activity on the Land described in Schedule 1, Item 2.

2.2 The Authority Holder must advise the Department of Conservation's local District Partnership Manager(s) one week prior to carrying out the Authorised Activity in the District, when the Authority Holder intends to carry out the Authorised Activity.

2.3 The Authority Holder and Authorised Personnel must carry a copy of this Authority with them at all times while carrying out the Authorised Activity.

2.4 Unless expressly authorised by the Grantor in writing, the Authority Holder must not donate, sell or otherwise transfer to any third party any material, including any genetic material, or any material propagated or cloned from such material, collected under this Authority. Notwithstanding the preceding constraint, the Authority Holder may publish authorised research results.

2.5 The Authority Holder must lodge holotype specimens and a voucher specimen with a recognised national collection any taxon, which is new to science. The Authority Holder must immediately notify the Grantor of any such finds.

3. Who is authorised?

3.1 Only the Authority Holder and the Authorised Personnel described in Schedule 1, Item 3 may be involved in carrying out the Authorised Activity, unless otherwise agreed in writing by the Grantor.

4. How long is the Authority for - the Term?

4.1 This Authority commences and ends on the dates set out in Schedule 1, Item 4.

5. What are the obligations to protect the environment?

5.1 Other than what is authorised by this Authority, the Authority Holder must not cut down or damage any vegetation; or damage any natural feature or historic resource on any public conservation land being part of the Land; or light any fire on such public conservation land; or erect any structure such public conservation land without the prior consent of the Grantor.

5.2 The Authority Holder must ensure that it adheres to the international "Leave No Trace" Principles at all times (www.leavenotrace.org.nz).

5.3 The Authority Holder must not bury:

(a) any toilet waste within 50 metres of a water source on any public conservation land being part of the Land; or

(b) any animal or fish or any part thereof within 50 metres of any water body, water source or public road or track.

6. What are the liabilities?

6.1 The Authority Holder agrees to exercise the Authority at the Authority Holder's own risk and releases to the full extent permitted by law the Grantor and the Grantor's employees and agents from all claims and demands of any kind and from all liability which may arise in respect of any accident, damage or injury occurring to any person or property arising from the Authority Holder's exercise of the Authorised Activity.

6.2 The Authority Holder must indemnify the Grantor against all claims, actions, losses and expenses of any nature which the Grantor may suffer or incur or for which the Grantor may become liable arising from the Authority Holder's exercise of the Authorised Activity.

6.3 This indemnity is to continue after the expiry or termination of this Authority in respect of any acts or omissions occurring or arising before its expiry or termination.

7. What about compliance with legislation and Grantor's notices and directions?

7.1 The Authority Holder must comply with all statutes, bylaws and regulations, and all notices and requisitions of any competent authority relating to the conduct of the Authorised Activity. Without limitation, this includes the Conservation Act and the Acts listed in the First Schedule of that Act and the Health and Safety in Employment Act.

7.2 The Authority Holder must comply with all reasonable notices and directions of the Grantor relating to the conduct of the Authorised Activity.

8. Are there limitations on public access and closure?

8.1 The Authority Holder acknowledges that the public conservation land being part of the Land is open to the public for access and that the Grantor may close public access to that public conservation land during periods of high fire hazard or for reasons of public safety or emergency.

9. When can the Authority be terminated?

9.1 The Grantor may terminate this Authority at any time in respect of the whole or any part of the Land, and/or the whole or any part of the Authorised Activity if:

(a) The Authority Holder breaches any of the conditions of this Authority; or

(b) in the Grantor's opinion, the carrying out of the Authorised Activity causes or is likely to cause any unforeseen or unacceptable effects.

9.2 If the Grantor intends to terminate this Authority in whole or in part, the Grantor must give the Authority Holder either:

(a) one calendar month's notice in writing; or

(b) such other time period which in the sole opinion of the Grantor appears reasonable and necessary in the circumstances.

10. How are notices sent and when are they received?

10.1 Any notice to be given under this Authority by the Grantor is to be in writing and made by personal delivery, fax, by pre paid post or email to the Authority Holder at the address, fax number or email address specified in Schedule 1, Item 5. Any such notice is to be deemed to have been received:

(a) in the case of personal delivery, on the date of delivery;

(b) in the case of fax, on the date of dispatch;

(c) in the case of post, on the 3rd working day after posting;

(d) in the case of email, on the date receipt of the email is acknowledged by the addressee by return email or otherwise in writing.

10.2 If the Authorised Holder's details specified in Schedule 1, Item 5 change then the Authorised Holder must notify the Grantor within 5 working days of such change.

11. What about the payment of costs?

11.1 The Authorised Holder must pay the standard Department of Conservation charge-out rates for any staff time and mileage required to monitor compliance with this Authority and to investigate any alleged breaches of the terms and conditions of it.

12. Are there any Special Conditions?

12.1 Special conditions are specified in Schedule 3. If there is a conflict between this Schedule 2 and the Special Conditions in Schedule 3, the Special Conditions shall prevail.

SCHEDULE 3

SPECIAL CONDITIONS

Use of species/materials/future use/disposal.

1. The Authority Holder must comply with any reasonable request from the Grantor for access by the Grantor or the Grantor's nominee to any collected species or material.

Private land

2. This Authority does not confer any right of access over any private land; or public conservation land leased by the Grantor (unless specified in the Authorised Activity). Any arrangements necessary for access over private land or leased land are the responsibility of the Authority Holder. In granting this Authority the Grantor does not warrant that such access can be obtained.

Expectations of the public

3. The Authority Holder must use best endeavours to ensure that the Authorised Activity is not undertaken within sight of the public.

4. While undertaking the Authorised Activity the Authority Holder must not exclude or impede the public from accessing any sites, tracks or facilities.

5. If approached by members of the public while carrying out the Authorised Activity, the Authority Holder shall provide an explanation of why the Authorised Activity is taking place.

Biosecurity General

6. The Authority Holder must take all precautions to ensure weeds and non-target species are not introduced to the Land; this includes ensuring that all tyres, footwear, gaiters, packs and equipment used by the Authority Holder, its staff and clients are cleaned and checked for pests before entering the Land.

Didymo

7. The Authority Holder must comply with the Ministry for Primary Industry (MPI)'s "Check, Clean, Dry" cleaning methods to prevent the spread of didymo (*Didymosphenia geminata*) and other freshwater pests when moving between waterways. "Check, Clean, Dry" cleaning methods can be found at - http://www.biosecurity.govt.nz/cleaning. The Authority Holder must regularly check this website and update their precautions accordingly.

Records

8. All records of the Authorised Activity shall be made available for inspection at reasonable times by officers of the Grantor.

Reporting

9. The Authority Holder shall provide an annual report to the Grantor. This report shall be electronically forwarded to the Grantor at raukapukaao@doc.govt.nz and permissionshamilton@doc.govt.nz, citing Authority number 42983-GEO. This report shall be submitted by the 31st of July detailing the period ending 30 June.

Variations

10. The Authority Holder may apply for variations to the Authority; this must be done by contacting the Permissions team where the original authorisation was processed.

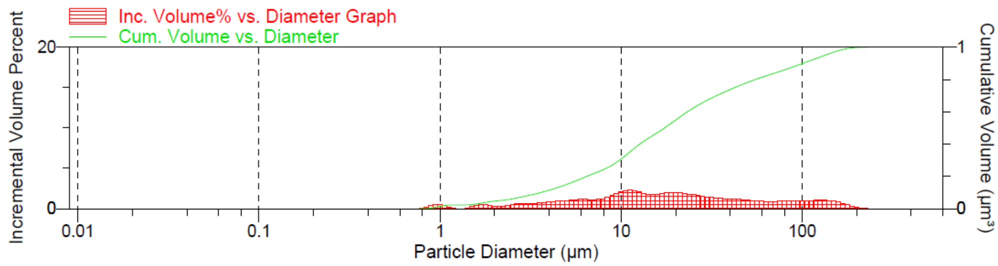
Appendix 3

Grain size analysis results

WLB1.1

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.00836 %
Obscuration: 13.9 %

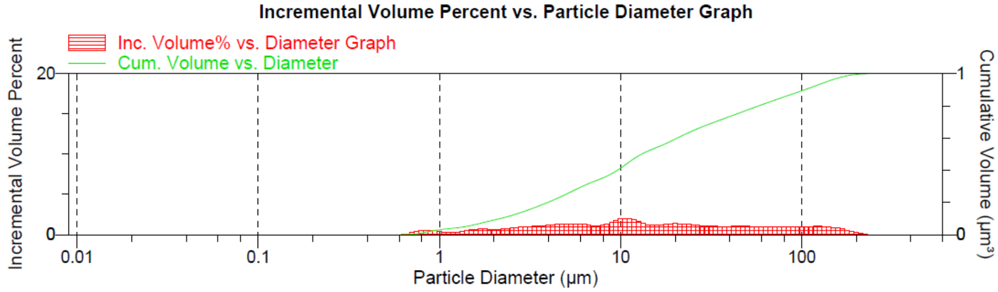
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	34.499	0.000	Mode	11.222	0.000
Median	17.345	0.000			

WLB1.2

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.00720 %
Obscuration: 17.0 %

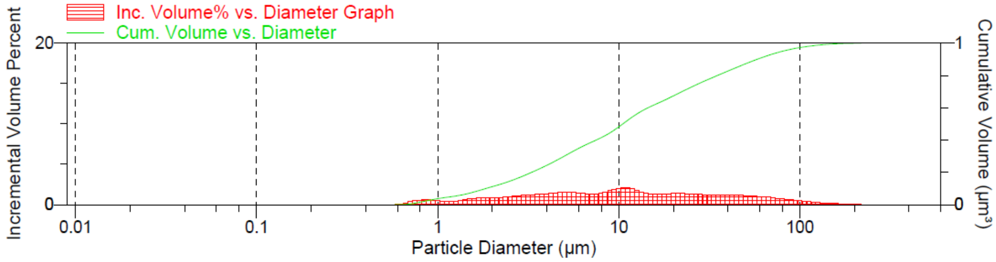
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	33.610	0.000	Mode	10.594	0.000
Median	13.037	0.000			

WLB1.3

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.00551 %
Obscuration: 15.5 %

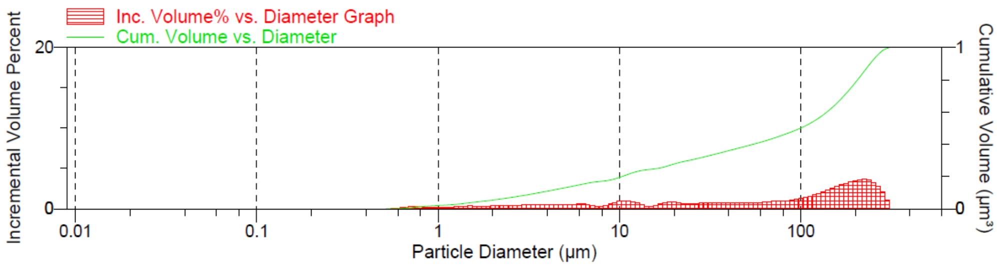
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	21.558	0.000	Mode	10.594	0.000
Median	10.508	0.000			

WLB1.4

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.01174 %
Obscuration: 15.9 %

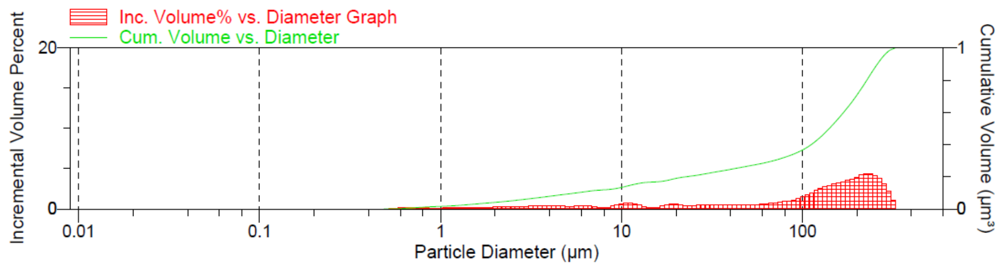
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	109.288	0.000	Mode	223.903	0.000
Median	99.454	0.000			

WLB1.5

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.01338 %
Obscuration: 13.8 %

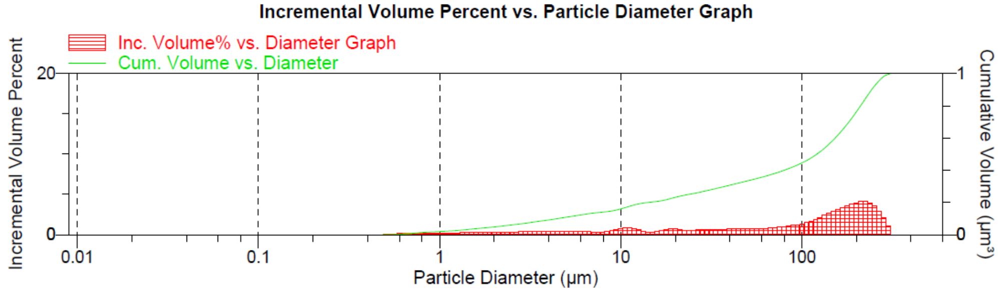
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	135.302	0.000	Mode	237.170	0.000
Median	140.592	0.000			

WLB1.6

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.01162 %
Obscuration: 14.0 %

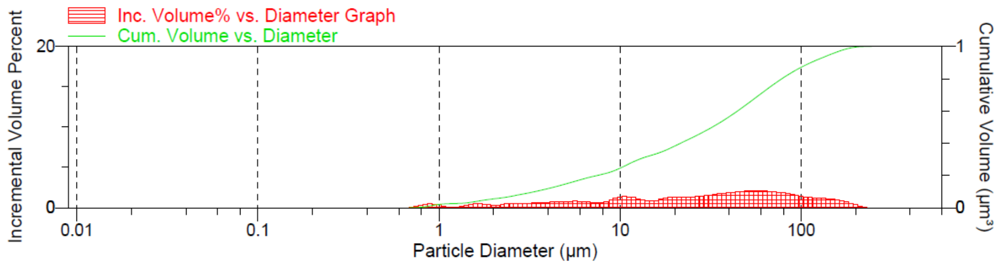
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	118.687	0.000	Mode	223.903	0.000
Median	120.864	0.000			

WLB1.7

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.00917 %
Obscuration: 14.2 %

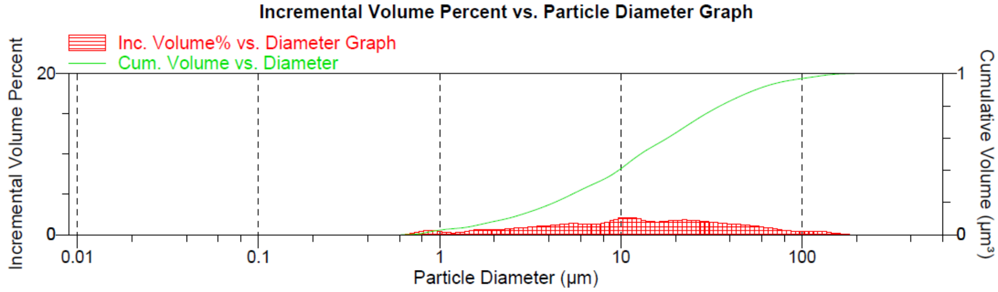
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	46.072	0.000	Mode	56.242	0.000
Median	32.272	0.000			

WLB1.8

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.00589 %
Obscuration: 13.8 %

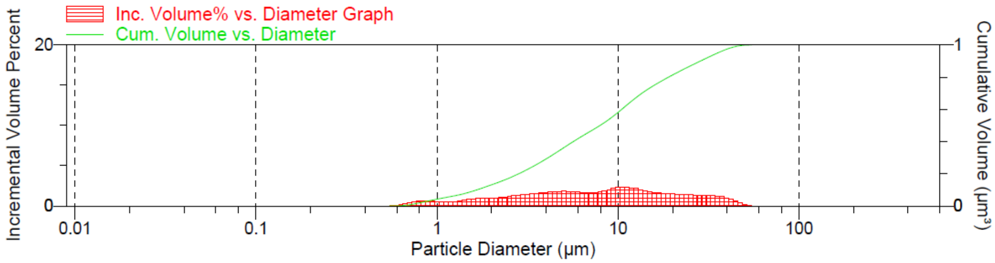
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	22.784	0.000	Mode	11.222	0.000
Median	12.798	0.000			

WLB1.9

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.00392 %
Obscuration: 13.2 %

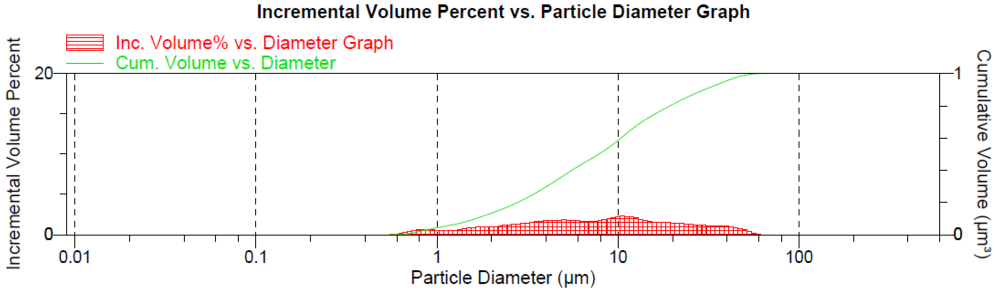
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	11.519	0.000	Mode	10.594	0.000
Median	7.945	0.000			

WLB1.10

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.00416 %
Obscuration: 14.1 %

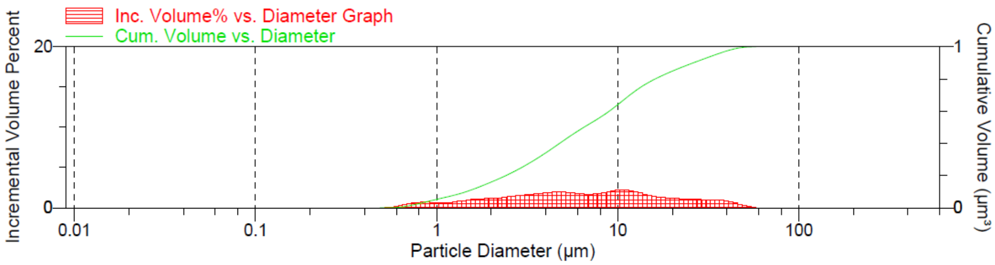
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	11.891	0.000	Mode	10.594	0.000
Median	7.819	0.000			

WLB1.11

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.00371 %
Obscuration: 14.2 %

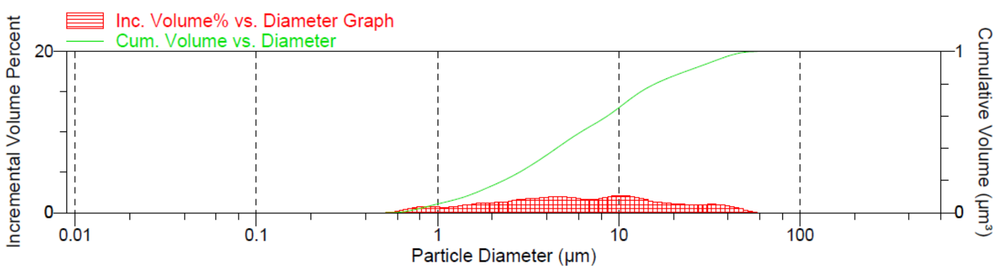
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	10.312	0.000	Mode	10.594	0.000
Median	6.495	0.000			

WLB1.12

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

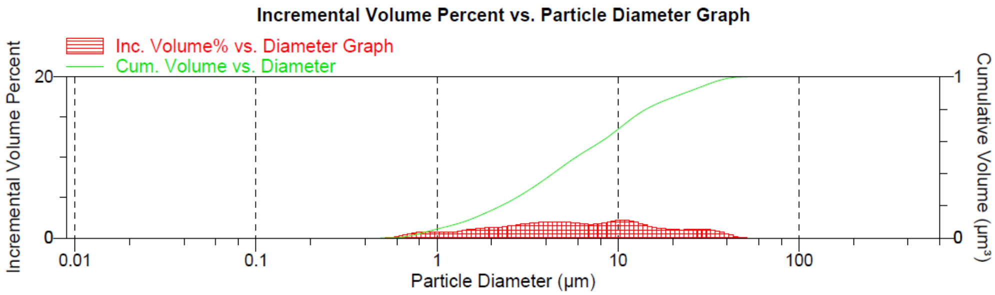
Sample Concentration: 0.00338 %
Obscuration: 13.3 %

Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	10.227	0.000	Mode	10.594	0.000
Median	6.148	0.000			

WLB1.13

Combined Report



Summary Report

Sample

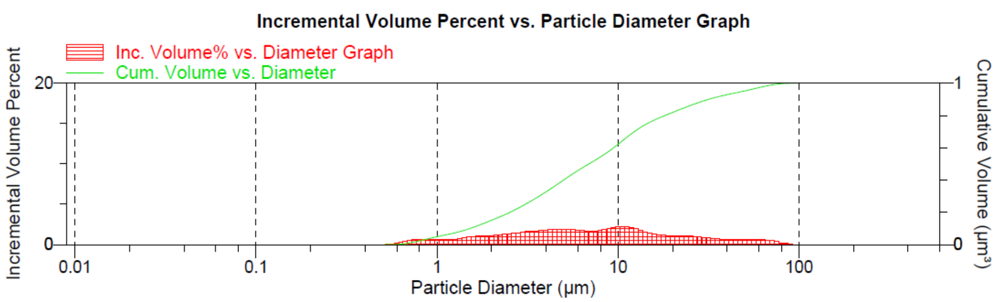
Sample Concentration: 0.00342 %
Obscuration: 13.8 %

Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	9.253	0.000	Mode	10.594	0.000
Median	5.824	0.000			

WLB1.14

Combined Report



Summary Report

Sample

Sample Concentration: 0.00409 %
Obscuration: 14.9 %

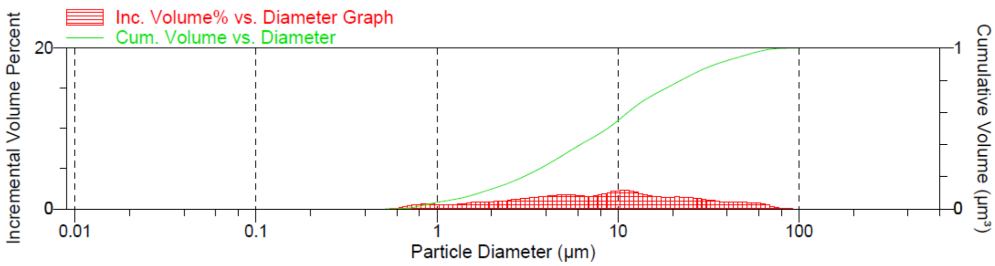
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	12.457	0.000	Mode	10.594	0.000
Median	6.887	0.000			

WLB1.15extra

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.00457 %
Obscuration: 14.3 %

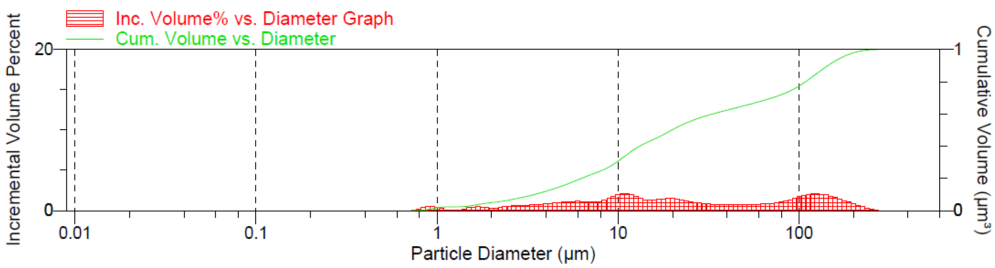
Weighted Statistics (Volume Distribution)

		Std Dev of 2			Std Dev of 2
Mean	13.928	2.080	Mode	10.908	0.444
Median	8.709	2.577			

WLB2.1

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

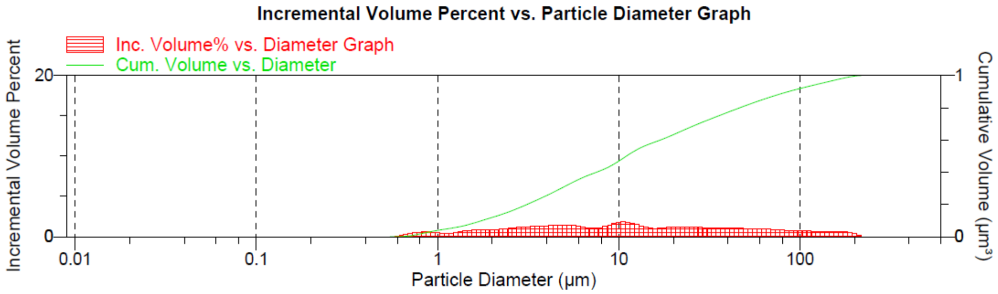
Sample Concentration: 0.00962 %
Obscuration: 15.6 %

Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	51.299	0.000	Mode	10.594	0.000
Median	19.795	0.000			

WLB2.2

Combined Report



Summary Report

Sample

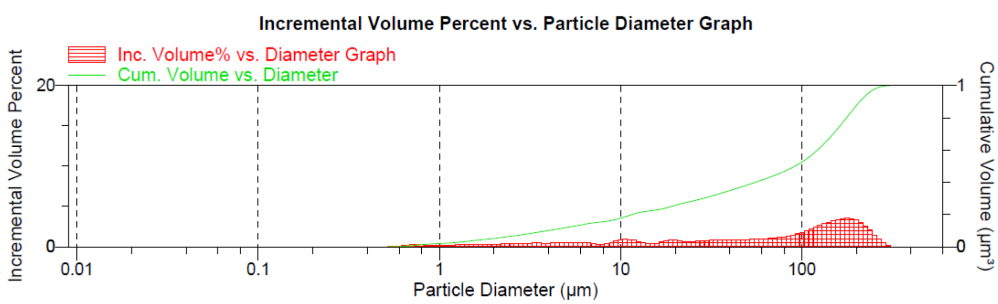
Sample Concentration: 0.00522 %
Obscuration: 15.0 %

Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	29.164	0.000	Mode	10.594	0.000
Median	10.999	0.000			

WLB2.3

Combined Report



Summary Report

Sample

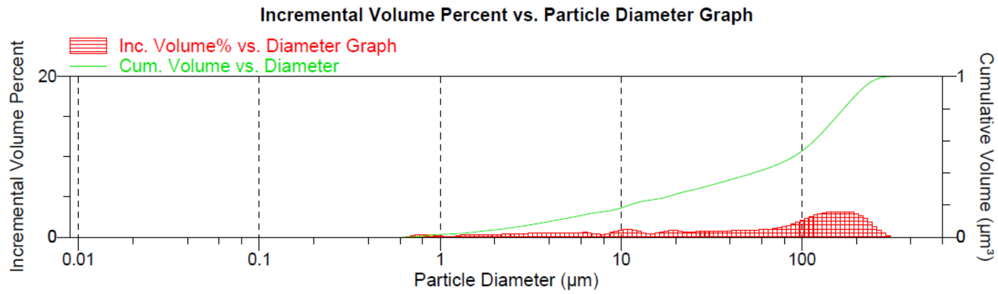
Sample Concentration: 0.01088 %
Obscuration: 14.2 %

Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	97.535	0.000	Mode	177.852	0.000
Median	91.480	0.000			

WLB2.4

Combined Report



Summary Report

Sample

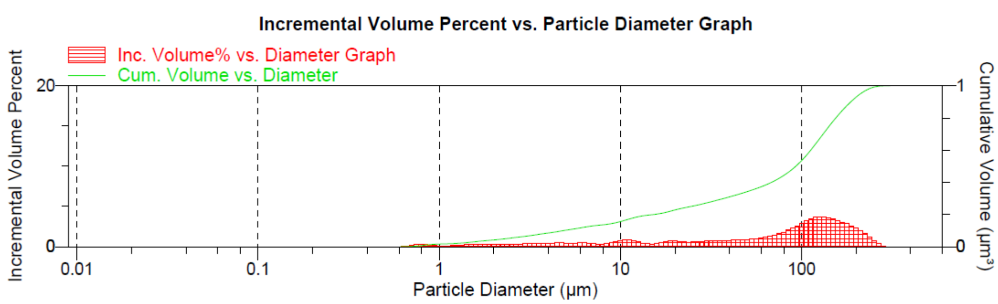
Sample Concentration: 0.01183 %
Obscuration: 14.3 %

Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	94.651	0.000	Mode	167.903	0.000
Median	89.175	0.000			

WLB2.5

Combined Report



Summary Report

Sample

Sample Concentration: 0.01268 %
Obscuration: 14.0 %

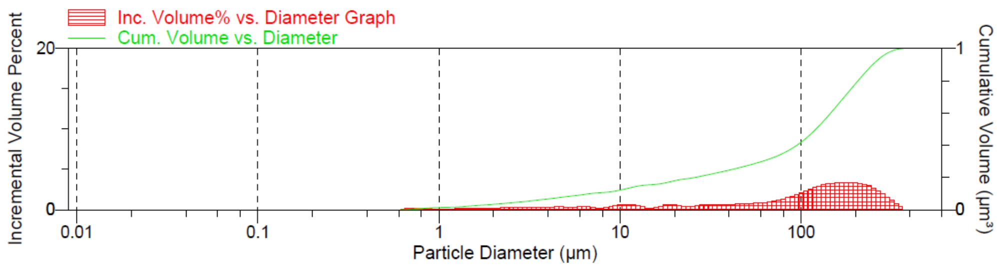
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	92.216	0.000	Mode	125.910	0.000
Median	92.775	0.000			

WLB2.6

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.01697 %
Obscuration: 15.1 %

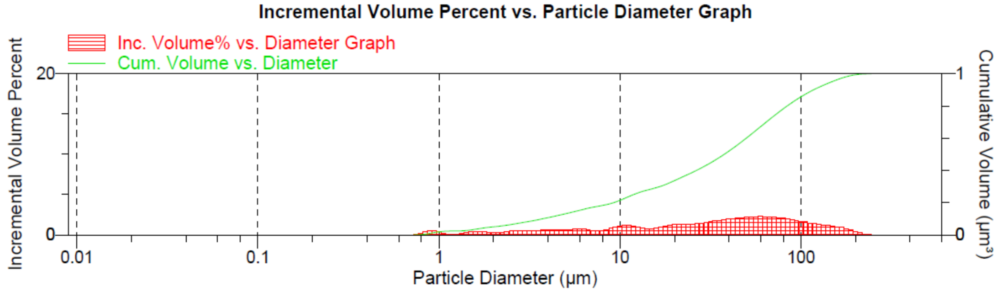
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	124.108	0.000	Mode	167.903	0.000
Median	120.812	0.000			

WLB2.7

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.00986 %
Obscuration: 13.9 %

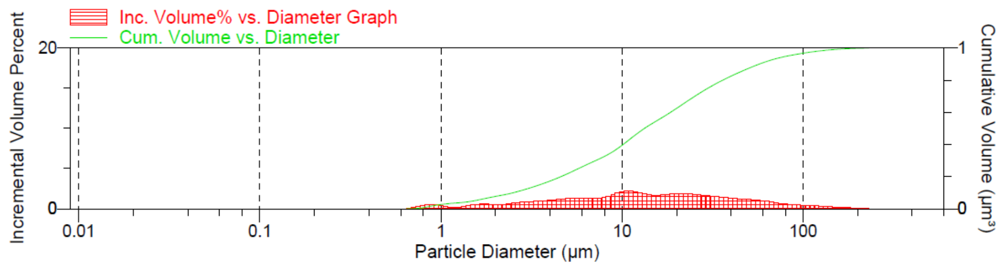
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	49.835	0.000	Mode	59.574	0.000
Median	37.617	0.000			

WLB2.8

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.00619 %
Obscuration: 13.9 %

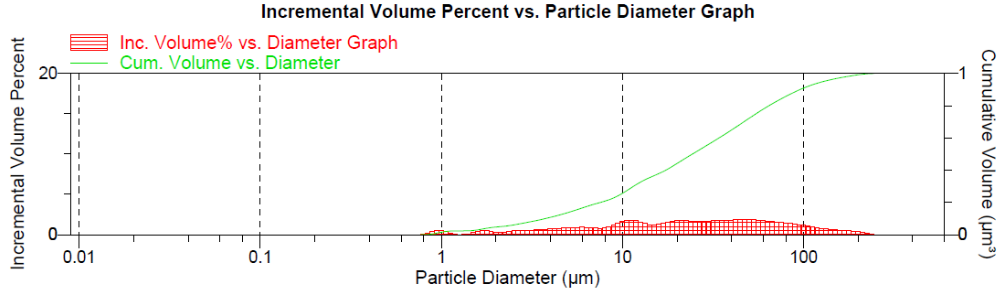
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	23.712	0.000	Mode	11.222	0.000
Median	13.287	0.000			

WLB2.9

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.00992 %
Obscuration: 14.9 %

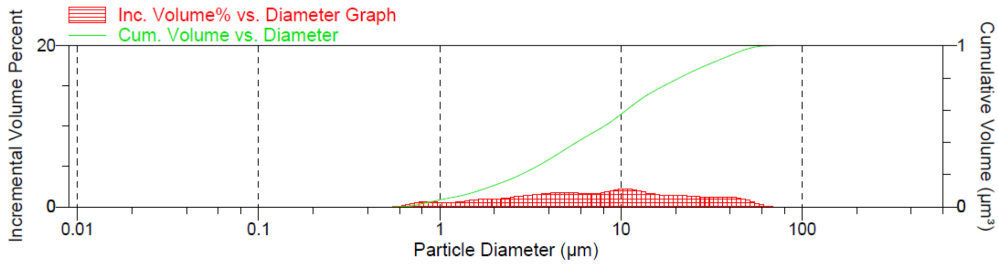
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	39.295	0.000	Mode	47.322	0.000
Median	24.293	0.000			

WLB2.10

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.00397 %
Obscuration: 13.4 %

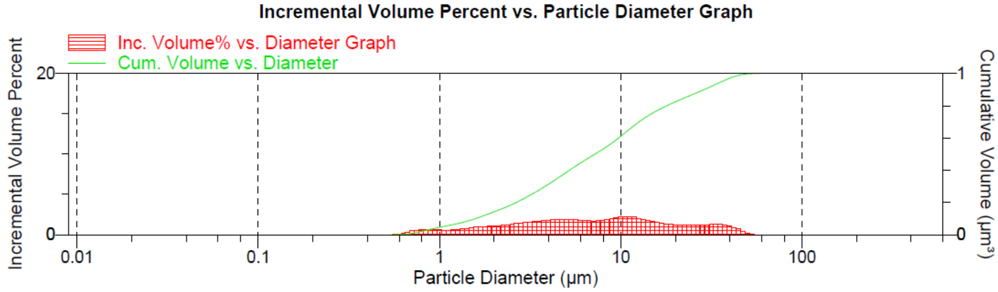
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	12.669	0.000	Mode	10.594	0.000
Median	8.046	0.000			

WLB2.11

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.00366 %
Obscuration: 13.0 %

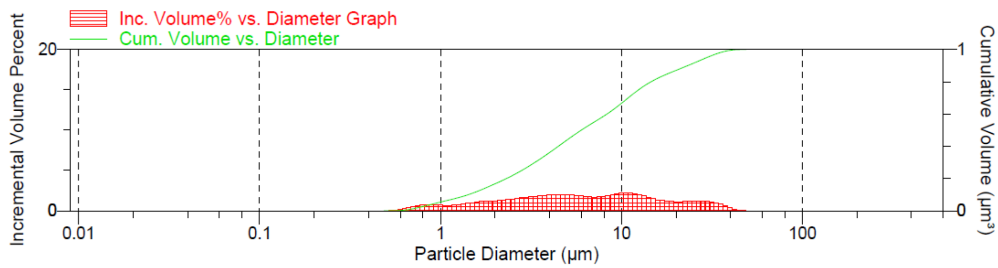
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	11.115	0.000	Mode	10.594	0.000
Median	7.194	0.000			

WLB2.12

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.00360 %
Obscuration: 14.3 %

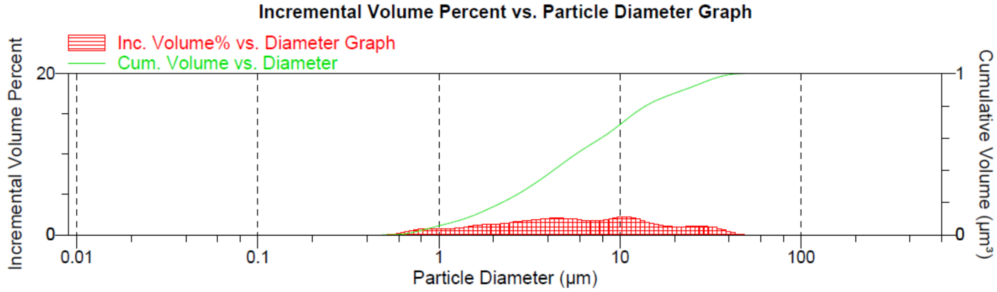
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	9.261	0.000	Mode	10.594	0.000
Median	5.986	0.000			

WLB2.13

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

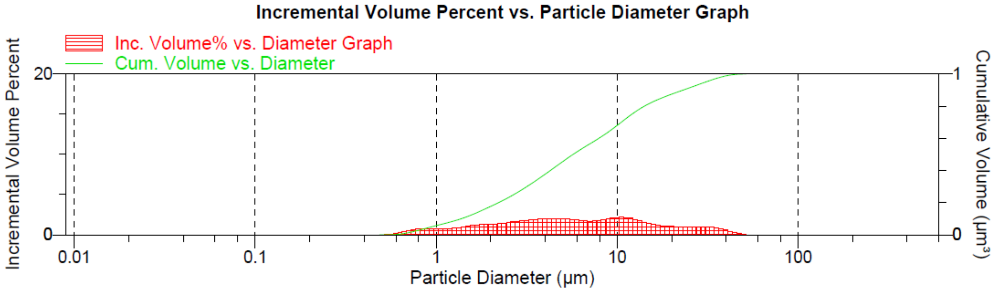
Sample Concentration: 0.00347 %
Obscuration: 14.2 %

Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	8.969	0.000	Mode	10.594	0.000
Median	5.681	0.000			

WLB2.14

Combined Report



Summary Report

Sample

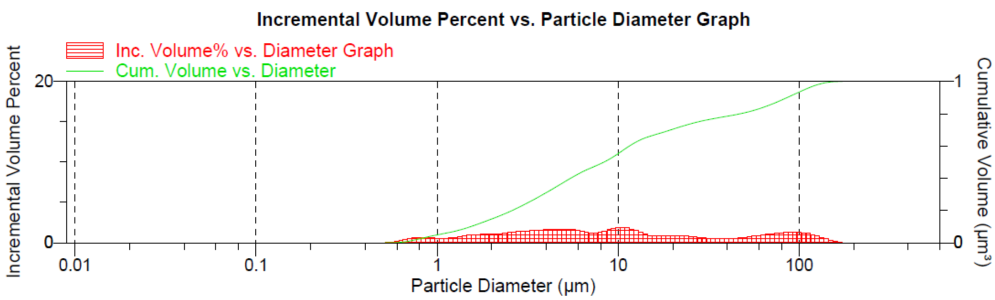
Sample Concentration: 0.00325 %
Obscuration: 13.4 %

Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	9.187	0.000	Mode	10.594	0.000
Median	5.704	0.000			

WLB2.15

Combined Report



Summary Report

Sample

Sample Concentration: 0.00509 %
Obscuration: 17.1 %

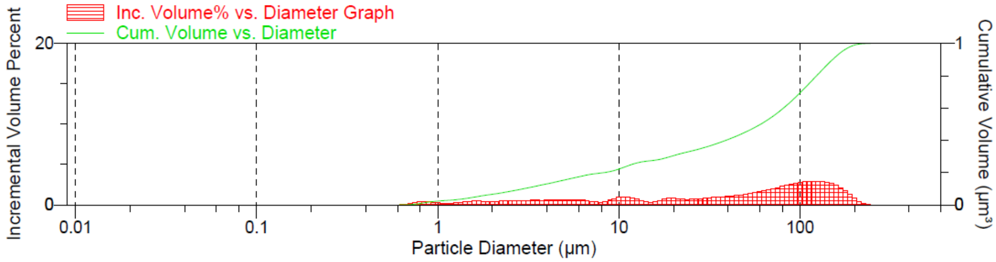
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	24.925	0.000	Mode	10.594	0.000
Median	8.336	0.000			

WLB2.16

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.00940 %
Obscuration: 14.6 %

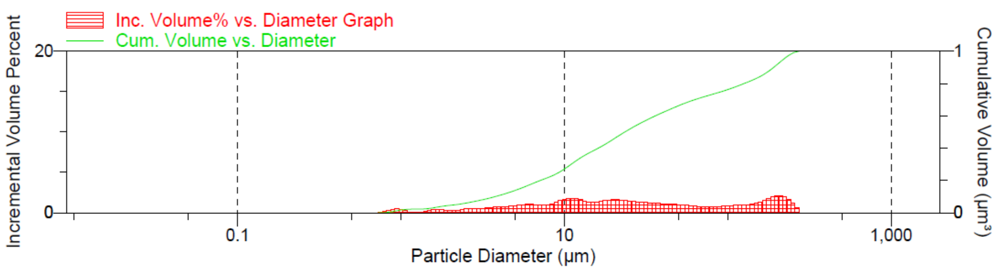
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	68.159	0.000	Mode	118.866	0.000
Median	60.507	0.000			

WLW1.1

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

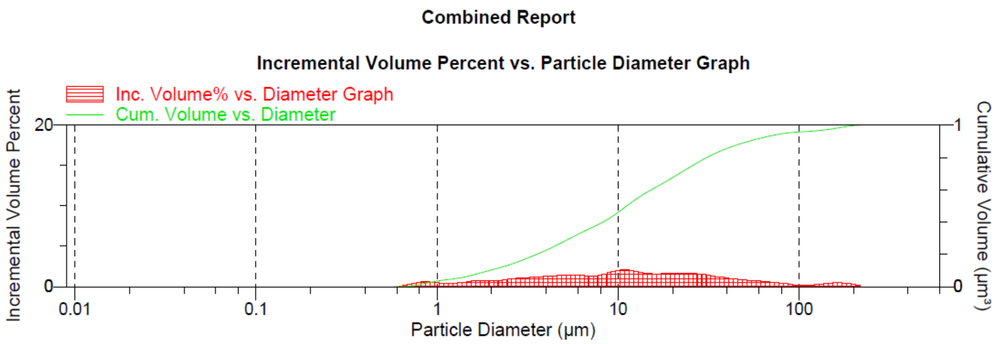
Sample

Sample Concentration: 0.00890 %
Obscuration: 13.5 %

Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	60.145	0.000	Mode	199.554	0.000
Median	23.453	0.000			

WLW1.2



Summary Report

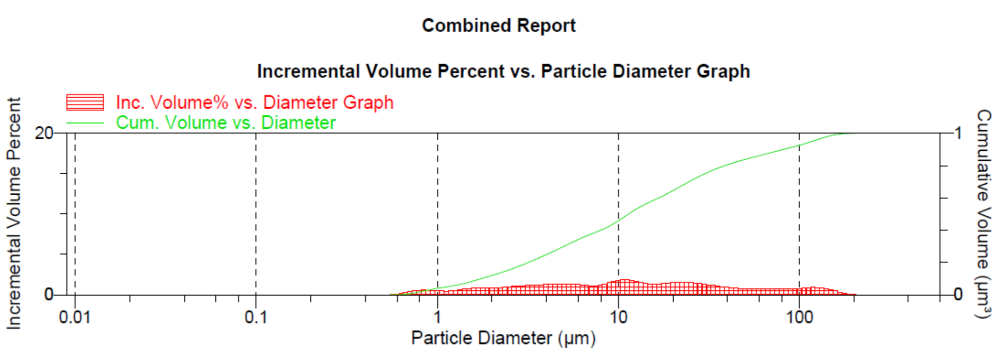
Sample

Sample Concentration: 0.00476 %
Obscuration: 12.9 %

Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	22.753	0.000	Mode	11.222	0.000
Median	11.167	0.000			

WLW1.3



Summary Report

Sample

Sample Concentration: 0.00513 %
Obscuration: 14.7 %

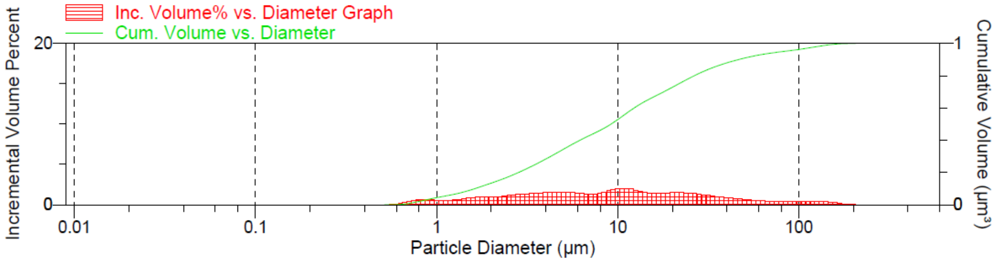
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	26.475	0.000	Mode	10.594	0.000
Median	11.354	0.000			

WLW1.4

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.00451 %
Obscuration: 14.3 %

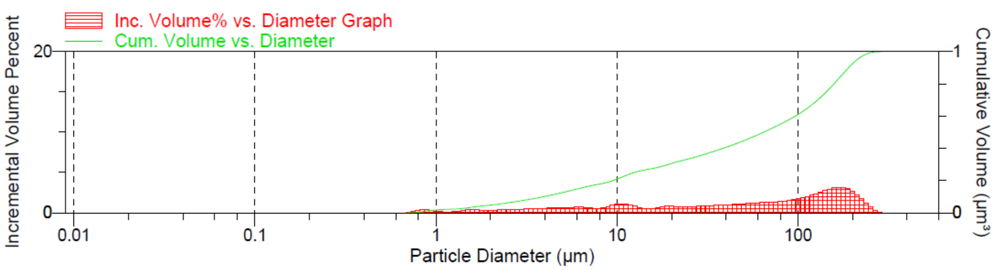
Weighted Statistics (Volume Distribution)

		Std Dev of 2			Std Dev of 2
Mean	19.120	10.402	Mode	10.594	0.000
Median	9.362	2.818			

WLW1.5

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.01084 %
Obscuration: 14.2 %

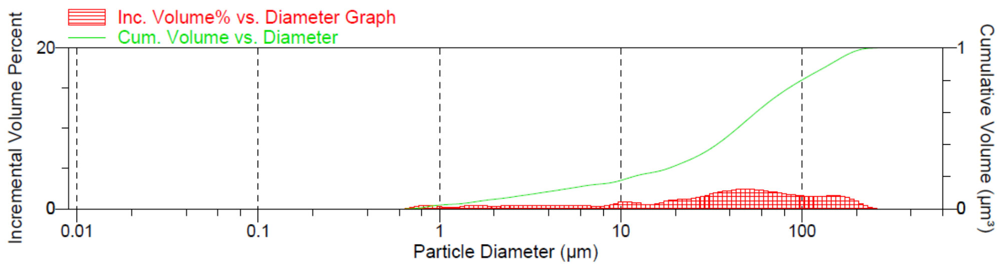
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	82.593	0.000	Mode	167.903	0.000
Median	64.351	0.000			

WLW1.6

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.01043 %
Obscuration: 14.6 %

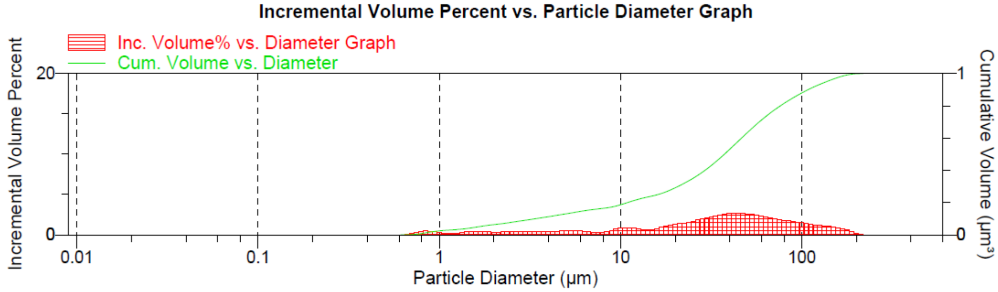
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	58.792	0.000	Mode	50.126	0.000
Median	43.907	0.000			

WLW1.7

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.00901 %
Obscuration: 13.6 %

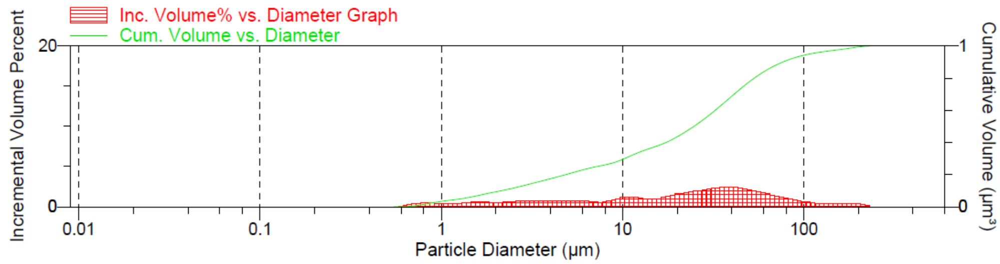
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	47.423	0.000	Mode	44.674	0.000
Median	37.368	0.000			

WLW1.8

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.00688 %
Obscuration: 14.9 %

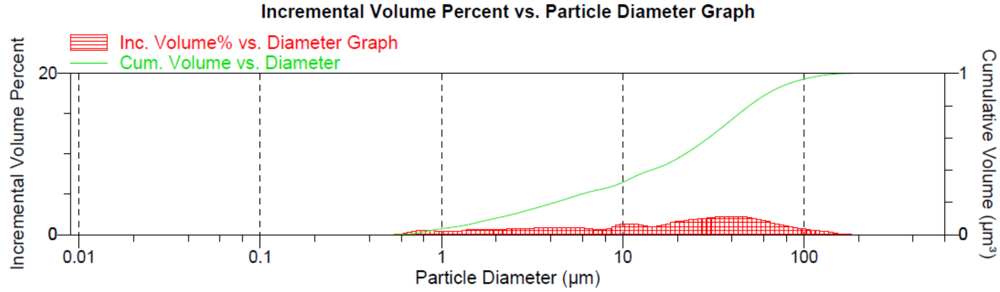
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	34.335	0.000	Mode	37.589	0.000
Median	24.695	0.000			

WLW1.9

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.00778 %
Obscuration: 17.9 %

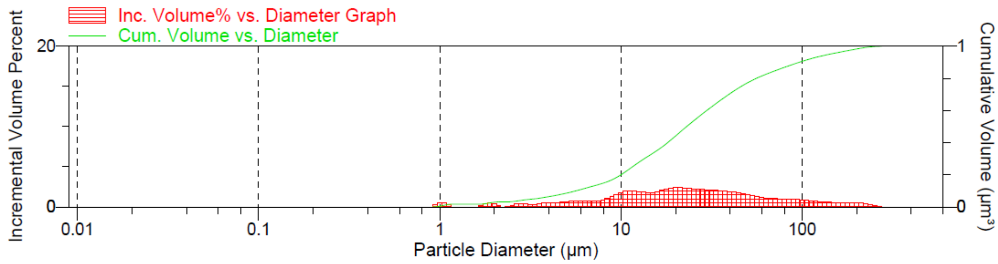
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	29.747	0.000	Mode	39.816	0.000
Median	22.000	0.000			

WLW2.1

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.01140 %
Obscuration: 13.7 %

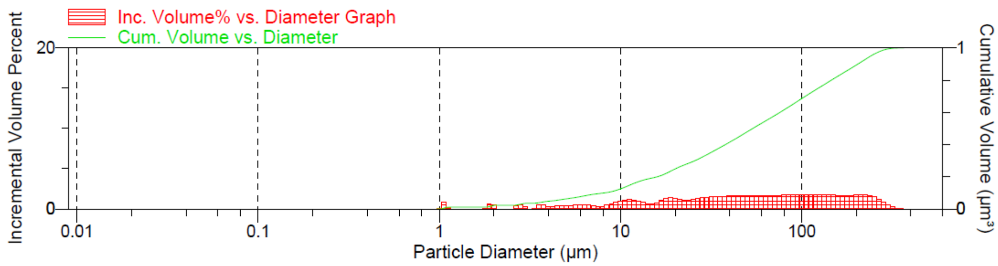
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	39.074	0.000	Mode	19.955	0.000
Median	23.000	0.000			

WLW2.2

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

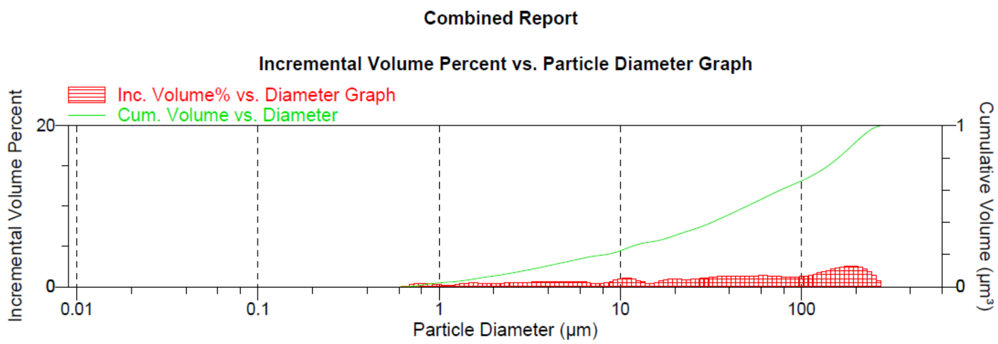
Sample

Sample Concentration: 0.02043 %
Obscuration: 16.3 %

Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	80.989	0.000	Mode	94.419	0.000
Median	53.606	0.000			

WLW2.3



Summary Report

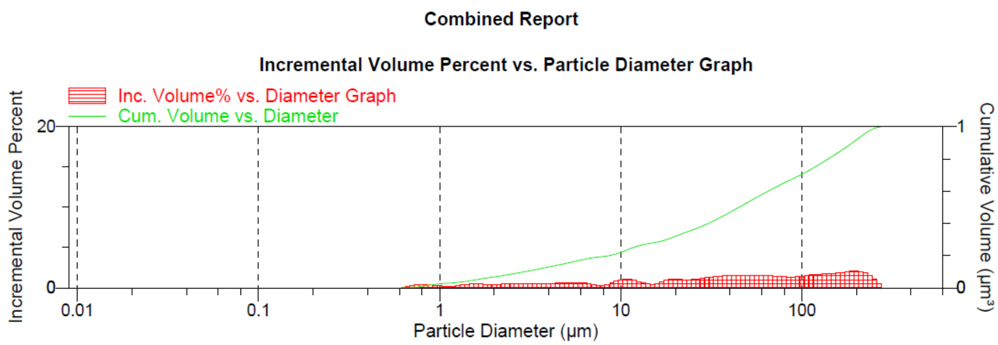
Sample

Sample Concentration: 0.00856 %
Obscuration: 13.6 %

Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	78.931	0.000	Mode	188.391	0.000
Median	49.904	0.000			

WLW2.4



Summary Report

Sample

Sample Concentration: 0.00961 %
Obscuration: 15.3 %

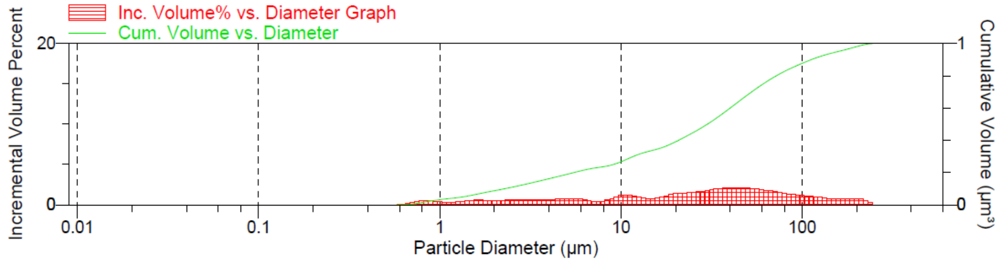
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	71.725	0.000	Mode	199.554	0.000
Median	44.844	0.000			

WLW2.5

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.00716 %
Obscuration: 14.3 %

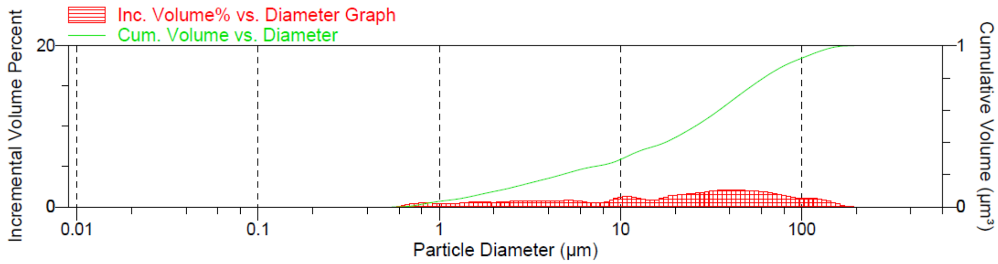
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	44.855	0.000	Mode	42.175	0.000
Median	29.946	0.000			

WLW2.6

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.00668 %
Obscuration: 14.5 %

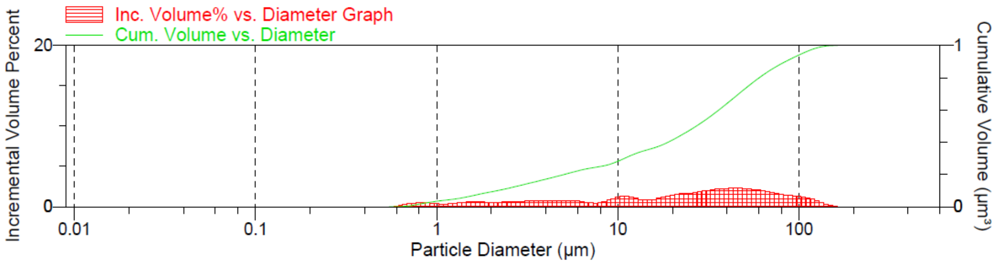
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	36.215	0.000	Mode	39.816	0.000
Median	25.719	0.000			

WLW2.7

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.00675 %
Obscuration: 14.3 %

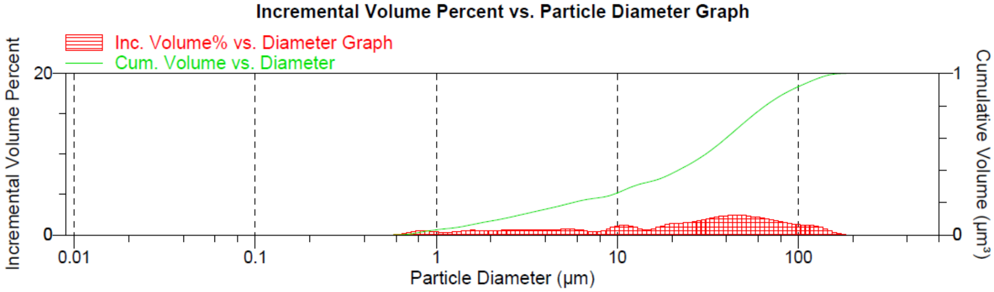
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	35.320	0.000	Mode	44.674	0.000
Median	27.074	0.000			

WLW2.8

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.00885 %
Obscuration: 17.2 %

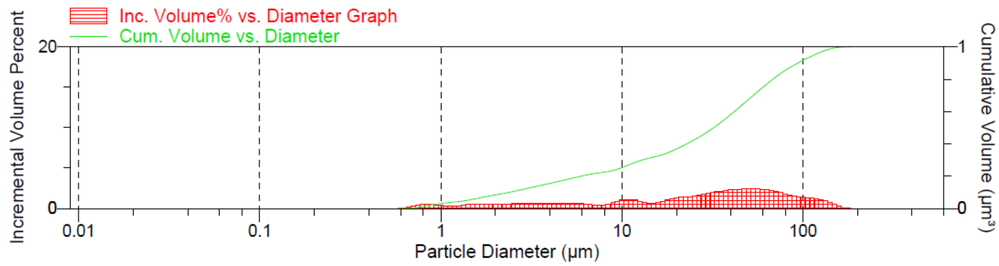
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	39.132	0.000	Mode	44.674	0.000
Median	30.662	0.000			

WLW2.9

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.00737 %
Obscuration: 14.2 %

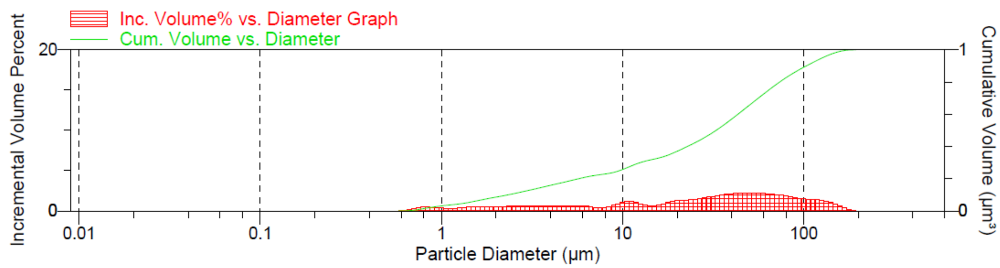
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	40.218	0.000	Mode	50.126	0.000
Median	32.101	0.000			

WLW2.10

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.00715 %
Obscuration: 14.0 %

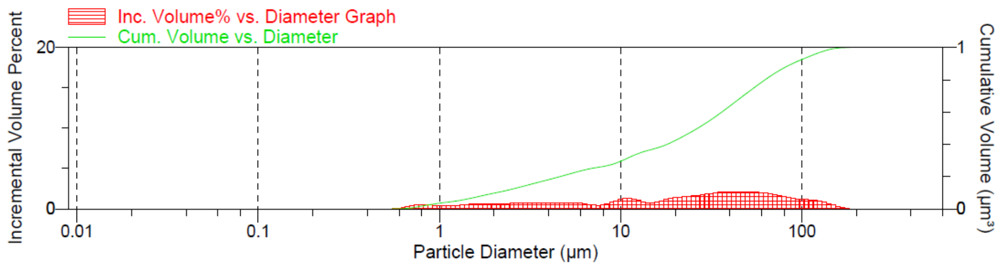
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	42.835	0.000	Mode	50.126	0.000
Median	32.774	0.000			

WLW2.11

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

Sample

Sample Concentration: 0.00613 %
Obscuration: 13.6 %

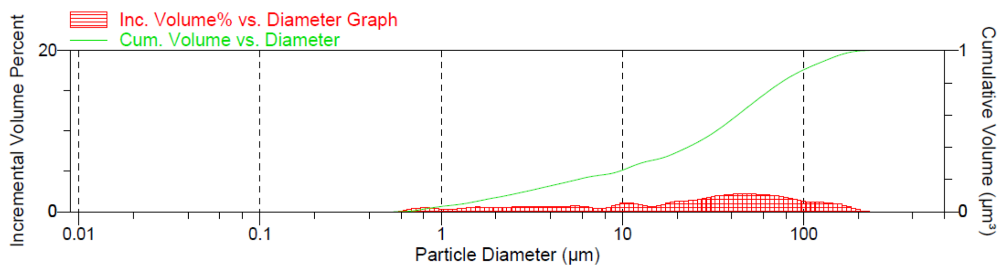
Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	36.476	0.000	Mode	42.175	0.000
Median	26.586	0.000			

WLW2.12

Combined Report

Incremental Volume Percent vs. Particle Diameter Graph



Summary Report

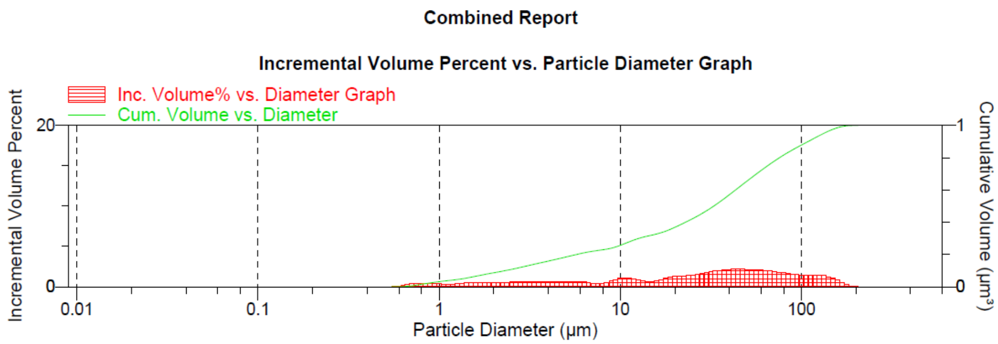
Sample

Sample Concentration: 0.00794 %
Obscuration: 15.6 %

Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	44.522	0.000	Mode	47.322	0.000
Median	32.773	0.000			

WLW2.13



Summary Report

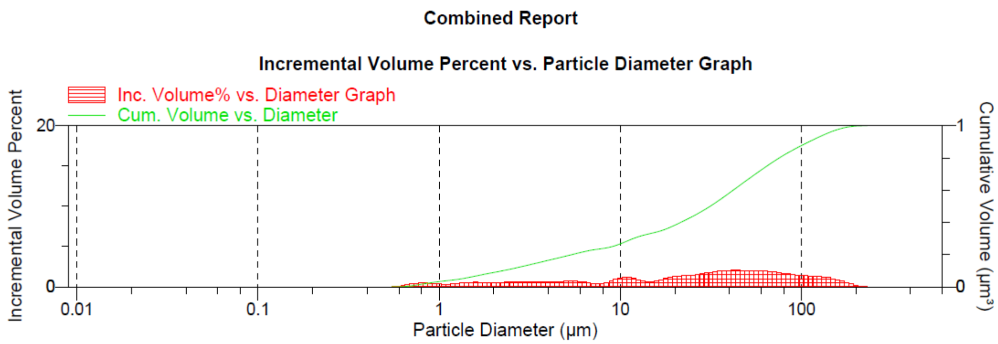
Sample

Sample Concentration: 0.00724 %
Obscuration: 14.2 %

Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	43.884	0.000	Mode	44.674	0.000
Median	32.759	0.000			

WLW2.14



Summary Report

Sample

Sample Concentration: 0.00692 %
Obscuration: 14.1 %

Weighted Statistics (Volume Distribution)

		Std Dev of 1			Std Dev of 1
Mean	43.885	0.000	Mode	42.175	0.000
Median	31.280	0.000			